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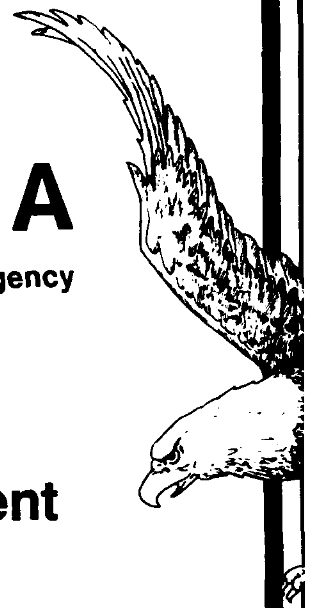

USATHAMA

U.S. Army Toxic and Hazardous Materials Agency

USATHAMA Installation Restoration Program Research and Development Strategies

March 1990

Prepared by
Environmental Management Operations

Prepared for the U.S. Army Toxic
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This report is the result of a study conducted for the U.S. Army Toxic and Hazardous Materials Agency (USATHAMA) to identify and prioritize potential research and development (R&D) activities that could reduce the cost of environmental restoration activities at Army installations where munitions production or tactical vehicle maintenance has been performed. In particular, the study examined potential R&D investments for restoration of soil and groundwater contaminated with explosives, heavy metals, and volatile organic compounds. Numerous new and innovative technologies that represent broad technology categories (physical, chemical, thermal, or biological processes) were considered in evaluating potential R&D investments for these restorations, and priorities for R&D investment were assigned to these technology categories.

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USATHAMA INSTALLATION RESTORATION PROGRAM RESEARCH AND DEVELOPMENT STRATEGIES

M. K. White
C. L. Fow

March 1990

Prepared for U.S. Army Toxic and
Hazardous Materials Agency
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1.0 INTRODUCTION

The purpose of this study was to identify and prioritize potential research and development (R&D) activities that could reduce the cost of environmental restoration activities at Army installations where munitions production or tactical vehicle maintenance has been performed.

1.1 BACKGROUND

The study was conducted for the U.S. Army Toxic and Hazardous Materials Agency (USATHAMA) by Environmental Management Operations (EMO).[a] USATHAMA, which is part of the Army Corps of Engineers, has the responsibility for centrally managing implementation of the Department of Army Installation Restoration Program (DA IRP) at current Army sites. The purpose of USATHAMA's Installation Restoration Decontamination Technology Development Program (Project AF25) is to provide R&D support for required assessment and cleanup activities at Army installations. Project AF25 funding is currently being supplemented with Defense Environmental Restoration Account (DERA) funding.

Current USATHAMA R&D efforts conducted for the DA IRP include the evaluation of commercially available state-of-the-art technology for installation restoration and development of new, innovative technology that is more economical and efficient than existing technology. The purpose of this report is to examine the potential payoff in DA IRP cost reduction for various types of new or innovative technologies that USATHAMA could develop to complement or replace existing technology. These evaluations will assist USATHAMA in prioritizing their current R&D investments and in estimating whether additional R&D investments would be cost effective.

1.2 SCOPE

The study examined potential R&D investments for a portion of the DA IRP activities. DA IRP activities considered were those for restoration of soil

(a) Environmental Management Operations is operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

or groundwater contaminated as a result of wastewater lagoon operations at Army installations where munitions production or tactical vehicle maintenance activities have been performed. These activities have resulted in the contamination of soil and groundwater with combinations of explosives (EXPs), heavy metals (HMs), and volatile organic compounds (VOCs).

The estimated reduction in costs for utilizing developmental rather than existing technologies for soil and groundwater cleanup for each contamination category was examined as a basis for identifying and prioritizing potential R&D investments. The cost estimates developed were based on the limited installation contamination data found in the USATHAMA and DA IRP documents examined. The cost information presented in this report should be considered preliminary data suitable for the purposes of this study, but it should not be considered as a basis for estimating the total cost for the soil and groundwater cleanup portion of the DA IRP. The individual estimates are based on very preliminary data, and important costs such as site characterization costs, administrative and management costs, and long-term monitoring costs are not included.

Although the activities considered in this study make up a significant portion of the overall DA IRP activities, they by no means constitute all of the required activities. Not only are additional sources and types of contamination likely to exist at the Army installations considered, but operations at other Army installations are likely to lead to additional DA IRP requirements. Therefore, the cost estimates presented in this report do not provide a comprehensive basis for estimating overall DA IRP cost.

Numerous new or innovative technologies were considered in evaluating potential R&D investments. These technologies were viewed as illustrative or representative of broad categories of technologies (e.g., physical, chemical, thermal, or biological processes) that might apply to the specific DA IRP activities considered. The list of technologies considered was not comprehensive, but it is reasonably representative of the potential performance and cost of the various technology categories. The specific technologies considered were those identified in the USATHAMA and DA IRP documents that were

reviewed for this study, augmented by a few developmental technologies that have been identified since those documents were prepared.

Most of the new or innovative technologies are in the early stages of development, and there are only limited preliminary performance and cost data available for them. The data for the various technologies within a category were evaluated as a basis for qualitative judgments about the technology category's potential to reduce the cost for DA IRP activities. It was beyond the scope of this study to identify specific technologies within a category for further development. Such identification would require ensuring that a comprehensive set of technologies is considered, and it would be followed by a more detailed comparison of the potential performance and cost. However, the assessment of the likelihood of successfully developing a technology category is sufficient for the purposes of this study.

1.3 APPROACH

The approach for this study is shown in Figure 1.1. The initial step in the analysis was to use USATHAMA and DA IRP data as a basis for identifying remedial action requirements and for estimating the expected unit costs for performing DA IRP activities if current or existing technologies were utilized.

Preliminary data describing the number, size, and contents of wastewater lagoons at Army installations involved in munitions production or tactical vehicle maintenance were used as a basis for estimating a portion of the EXPs-, HMs-, or VOCs-contaminated soil or groundwater that might require treatment. The variation in the potential amount of contaminated soil or groundwater per installation for the sources considered that might require treatment for each contamination category, the range of total contaminated soil or groundwater in each category, and the assumed levels of soil and groundwater contamination were estimated.

USATHAMA and DA IRP data (supplemented by cost data from other applications of existing or current technology) were also utilized to estimate unit treatment costs. These data were used to identify the components of the potential IR cost (e.g., excavation/water extraction, treatment, disposal of

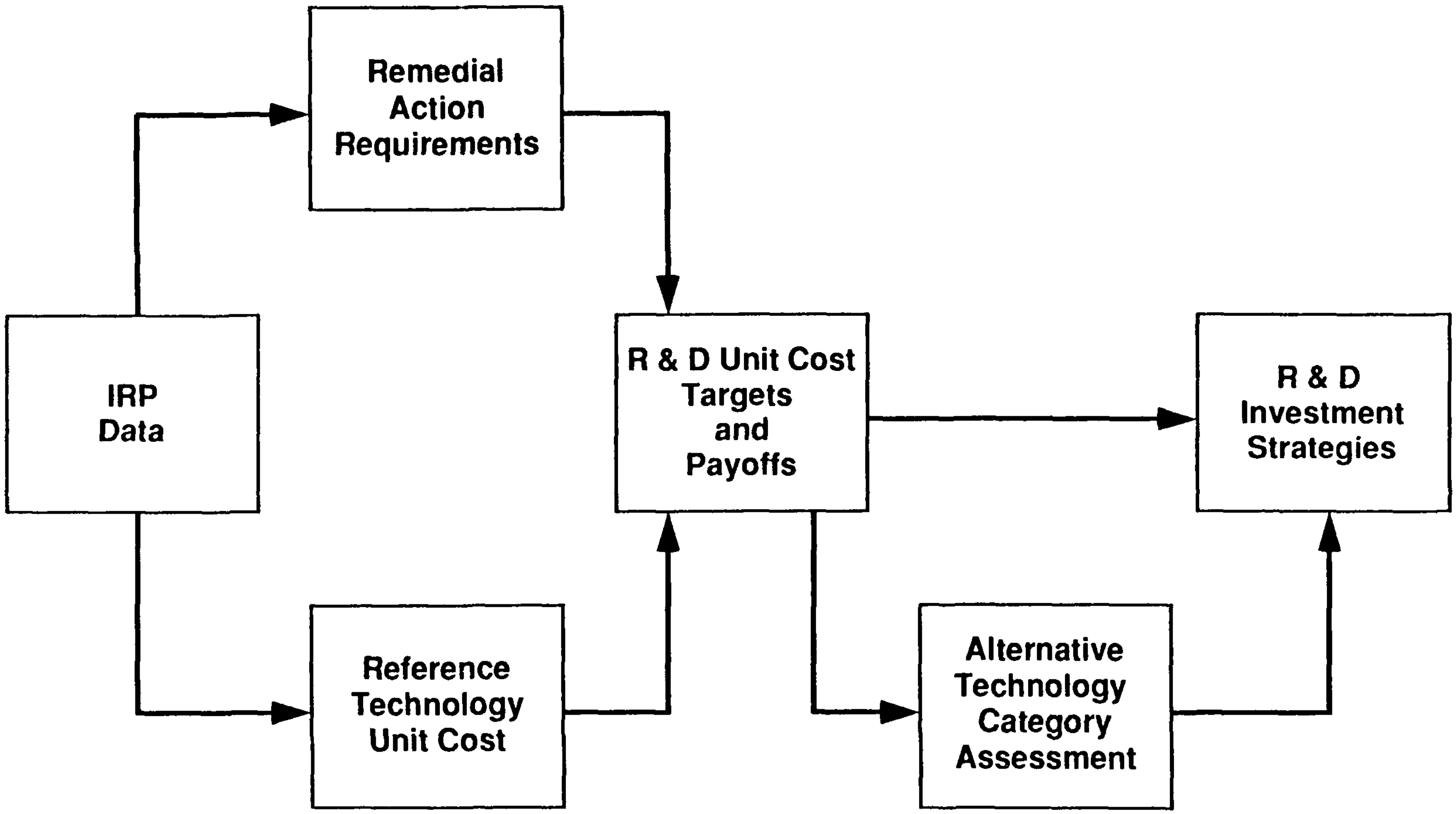

FIGURE 1.1. Technical Approach for Identifying R&D Investment Priorities

treated soil or groundwater, etc.) and to determine the sensitivity of unit costs to process or treatment rates and contamination levels.

The resulting partial estimates of remedial action requirements and technology costs were used to identify and compare potential opportunities for new or innovative technologies to reduce DA IRP cost. The potential for installation remediation (IR) program cost reduction was examined for each of the six remedial action categories individually (EXPs, HMs, or VOCs contamination in either soil or groundwater). A category's attractiveness as a candidate for a new or innovative technology to reduce DA IRP cost generally depended on both the extent of the potential remedial actions required (total amount of contaminated soil or groundwater to be treated) and the magnitude of the unit costs for the required excavation or extraction, treatment, or secondary waste disposal costs. In many cases, the relevant unit costs were functions of the process or treatment rates, so the distribution of required remedial actions by size (contaminated soil or groundwater per installation) was important for determining appropriate unit costs.

In general, new or innovative technologies must have the potential to substantially reduce these unit costs to be promising for reducing overall DA IRP cost. Target unit costs for developmental technologies were determined by comparing them with corresponding reference technology unit costs. The estimated cost reduction afforded by a new or innovative technology, if it achieves the target cost, depends on how much it reduces the corresponding unit cost for existing or currently used technology, and the extent to which the new or innovative technology can be applied in the DA IRP. Since there is considerable uncertainty in both of these factors, broad ranges of potential savings were estimated for the various technology categories.

The potential that new or innovative technologies have to reduce DA IRP cost (meeting target unit costs) was assessed by evaluating broad categories of potential technologies in order to estimate the likelihood that they could meet the required unit cost target. For each of the remedial action categories considered (soil or groundwater contaminated with EXPs, HMs, or VOCs), potential new or innovative technologies were identified for the broad general categories of physical, chemical, thermal, or biological technology.

The technologies identified for each of these technology categories were assumed to be representative of the comprehensive set of such technologies and were used to assess the likelihood that the category could achieve the relevant unit cost target for a remedial action category.

Two primary factors were considered in evaluating a technology category's potential for reducing DA IRP cost. The first factor was the range of anticipated unit costs for the new or innovative technologies representing the technology category. Categories for which several representative technologies may have unit costs less than the target unit cost were deemed more likely candidates for development. The second was the technological maturity of the representative technologies for the category. Categories with more fully demonstrated technologies were deemed more likely candidates for development. These judgments are by their nature qualitative and were made subjectively based on previous research experience.

After composite technological maturity and potential unit cost judgments were made for each relevant technology category for a remedial action category, a range of probabilities of achieving the target unit cost was estimated for each technology category based on those judgments. Technology categories with lower anticipated unit cost and more mature technologies were assumed to be more likely to meet the required development target unit cost. These probability ranges were then used in conjunction with previous results for DA IRP cost savings to probability weight the estimated savings (cost reduction) for developing that technology category. Both the absolute and probability-weighted estimated savings were considered in determining R&D investment priorities.

The technology categories were rank ordered in terms of payoff and probability-weighted payoff. Probability-weighted payoff is a measure of how much profit (or savings), on the average, each R&D investment is expected to yield. The preferred investment strategy in terms of DA IRP cost reduction is to invest in developing the categories in this order. The number of categories that can be developed depends on the level of R&D funding: the more R&D funding that is available, the more categories that can be developed and the greater will be the potential reduction in DA IRP cost. This ordering

and the estimation of the corresponding DA IRP savings constitute the major results of this study, which are 1) identification of the preferred order or priority for investing R&D funding in the various technology categories and 2) estimated DA IRP savings for varying levels of USATHAMA R&D funding for this portion of the overall DA IRP.

1.4 REPORT CONTENTS

The key results and findings of this study are described in Section 2. Section 3 contains estimates for the volume of contaminated soil for each remedial action category; discussion of the unit costs for appropriate existing or current technology for excavation, treatment, and secondary waste disposal; and identification of the target unit costs for developmental technologies and the corresponding payoffs. Section 4 has similar information for contaminated groundwater. Section 5 describes the evaluation of the alternative developmental technology categories. Section 6 describes how preferred investment strategies were identified.

2.0 SUMMARY

The purpose of this study was to identify and prioritize the potential USATHAMA R&D investments that could reduce costs for the DA IRP. The potential payoffs (DA IRP cost reductions relative to R&D investment levels) corresponding to various levels of USATHAMA R&D funding are examined, based on the assumption that R&D funding is allocated consistently with cost reduction priorities.

As a basis for evaluating potential R&D investments, this study examines estimated unit costs for potential DA IRP soil and groundwater remedial actions associated with wastewater lagoons, trenches, ditches, or impoundments at Army installations that have conducted munitions production or tactical vehicle maintenance operations. While these are not the only contamination sources that may result in DA IRP remedial actions, they are a significant fraction. Moreover, there are currently more data available for estimating remedial action requirements for these sources than for other sources. However, as can be seen by examining the remedial action requirement estimates in this report, even the data that are available for these sources is very preliminary and do not allow precise estimation of potential requirements.

Operation of such wastewater lagoons, trenches, ditches, or impoundments can result in soil or groundwater contamination by EXPs, HMs, and VOCs, and it is expected that environmental cleanup activities will be required for at least some of these installations as part of the DA IRP. Tables 2.1 and 2.2 summarize the estimated volumes of contaminated soil and groundwater for the installations considered for this study. The assumptions and data for the estimates in Tables 2.1 and 2.2 are discussed in Sections 3 and 4, respectively.

Even though these estimates correspond to only a portion of the potential requirements for remedial actions and have significant uncertainties associated with them, they are used in this study as the basis for comparing the potential of various categories of technologies to reduce DA IRP costs. Use of these limited data will probably result in underestimating the total

TABLE 2.1. Estimated Volumes of Contaminated Soil at Army Installations Based on Currently Available Data

	Contamination Category		
	Explosives	Heavy Metals	Volatile Organics
Number of Installations Identified from Data Examined as Having Contaminated Soil	28	14	8
Estimated Volume of Contaminated Soil (tons)			
Lagoons, Ditches, Trenches, or Impoundments	~1,000,000	~210,000	~180,000
Burning Grounds	?	?	?
Area Around Facilities	?	?	?
Other Installations	?	?	?
TOTAL (±20%)	>1,000,000	>210,000	>180,000

TABLE 2.2. Estimated Volume of Contaminated Groundwater at Army Installations Based on Currently Available Data

	Contamination Category		
	Explosives	Heavy Metals	Volatile Organics
Number of Installations Identified from Data Examined as Having Contaminated Groundwater	16	7	9
Assumed Treatment Rate, gpm	100 to 400	100 to 3000	400 to 3000
Assumed Treatment Time, years	20+	20+	20+
Estimated Volume of Contaminated Groundwater Treated, billions of gallons			
Current Installations and Assumptions	20 to 70	10 to 70	10 to 280
Treatment Beyond 20 Years	?	?	?
Other Installations	?	?	?
TOTAL VOLUME	>20 to 70	>10 to 70	>10 to 280

potential savings that could be realized for the DA IRP. The assumption for this study is that the potential savings estimates based on comprehensive data (if the data were available for all sources) for each type of remedial action would be in the same relative proportions as the estimates based on the available data. This assumption will hold if, as suggested by the estimates in Tables 2.1 and 2.2, the actual amount of soil contaminated with EXPs and groundwater contaminated with VOCs that is ultimately treated as part of the DA IRP is several times greater than the amount of the other contaminated soil and groundwater treated. Both of these assumptions seem likely based on what is currently known about DA IRP remedial action requirements.

The estimated unit costs for performing DA IRP remedial actions is used as a basis for estimating the portion of the potential DA IRP cost savings. Cost savings are calculated assuming that existing or current technologies are utilized and new or innovative technology can be successfully developed to reduce these unit costs. The reference technologies that are currently assumed are shown in Table 2.3. The technologies identified in Table 2.3 are all currently in common usage for similar remedial actions.

The unit costs for current technologies were used as the basis for determining appropriate unit cost targets for new or innovative technologies. Selected unit cost targets for alternative technologies were lower than the estimated unit costs for the reference technologies so that DA IRP cost reductions would be realized. However, these unit cost targets were not set so low as to be unrealistic or unachievable targets for development of alternative technologies. The assumptions and data for estimating unit costs for the reference soil and groundwater remedial action technologies are discussed in Sections 3 and 4, respectively.

Table 2.4 shows the unit cost targets that were adopted for each remedial action category. These unit cost targets, estimated unit costs for current technology, and the ranges of remedial action requirements shown in Tables 2.1 and 2.2 were used to estimate potential DA IRP cost reductions if the proposed unit cost targets can be achieved. These estimated potential savings are shown in Table 2.4. The estimated DA IRP cost reductions, or payoffs for successful development of alternative technologies, are broad

TABLE 2.3. Currently Assumed Remedial Action Technologies

	Contamination Category		
	Explosives	Heavy Metals	Volatile Organics
Soil Remedial Actions	Incineration	Offsite Disposal	In Situ Volatilization or Low Temperature Thermal Stripping
Groundwater Remedial Actions	Granular Activated Carbon	Precipitation or Ion Exchange	Air Stripping and Vapor-Phase Carbon

ranges based on uncertainties in both the current unit costs and the remedial action requirements. As previously noted, these estimated payoffs are likely to be lower than what could actually be realized because the estimates for remedial action requirements are not comprehensive. The soil and groundwater remedial action technology unit cost targets and corresponding payoffs are discussed in Sections 3 and 4.

Also shown in Table 2.4 are 1) the technology categories that were identified as candidates for yielding a technology that could meet the unit cost target for each remedial action category and 2) the relative likelihood of meeting the unit cost target for each technology category. Broad categories of technology (physical, chemical, thermal, and biological) were evaluated based on representative technologies that are currently identified for each. The judgments about the likelihood of a category yielding a technology that could meet the unit cost target are based on the relative number of identified technologies that appear to have promise for meeting the unit cost target and the maturity of the representative candidate technologies. Broad ranges of probability were assigned to the judgments about the relative likelihood of identifying and successfully developing a candidate technology from a technology category based on previous technology development experience. In this report, when the likelihood of identifying and developing a

TABLE 2.4. Summary of Developmental Technology Unit Costs, DA IRP Savings, and Technology Category Rankings

Remedial Action Category	Target Unit Cost	Estimated DA IRP Cost Savings (10^6)(b)	Technology Category Rankings(a) Physical	Chemical	Thermal	Biological
Soil						
Explosives	$100/ton	$100 to $300	-	MEDIUM	-	MEDIUM
	$50/ton	$150 to $350	-	LOW	-	-
Heavy Metals	$200/ton	$20 to $35	MEDIUM	LOW	LOW	-
	$300/ton	less than $10	MEDIUM	LOW	HIGH	-
Volatile Organic Compounds	$50/ton	$20 to $30	-	LOW	MEDIUM	MEDIUM
Groundwater (Onsite)						
Explosives						
Onsite	$1.50/Kgal	$30 to $175	MEDIUM	LOW	-	LOW
In situ	$0.08/gal	$25 to $450	-	-	-	LOW
Heavy Metals	$1.00 to $7.00/Kgal	$10 to $140	LOW	-	-	LOW
Volatile Organic Compounds						
Onsite	$0.20 to $0.70/Kgal	$10 to $140	-	LOW	-	LOW
In situ	$0.04/gal	$15 to $770	-	-	-	LOW

(a) "HIGH" ranking means that there is an estimated 50% to 70% likelihood of successfully identifying and developing a technology from that category to meet the unit cost target. "MEDIUM" and "LOW" rankings are estimated to have 30% to 40% likelihood and 10% to 15% likelihood, respectively, of similar success. No entry means no technologies were identified that would meet the unit cost target.

(b) Estimated savings for the portion of overall DA IRP remedial action requirements discussed in Sections 3.2 and Section 4.2. Additional remedial action requirements for contamination from other sources or at other installations could increase estimated savings.

technology is described as low, medium, or high, it refers to the definitions in Table 2.4. The evaluation of these technology categories is discussed in Section 5.

The estimated range of potential payoffs, along with the estimates for the likelihood of achieving those payoffs, were used to prioritize investments in the various technology categories. The resulting priorities were assessed on the bases of both potential payoff and probability-weighted payoff for each technology category. Probability-weighted payoff is the estimated savings that would be realized, on the average, for each of a number of investments which have the estimated payoff and a probability of success. Probability-weighted payoff is therefore a measure of how much would be realized for a typical investment with the estimated probability and payoff. Although the probability that a technology will succeed is subjective, it was as carefully defined as possible for this study based on previous research and accepted methods (see Section 5 and Section 6.3). This probability estimate is determined by the judgment of experienced researchers, and because the probability estimate is subjective, a range of percentages was used when the technologies were ranked for the likelihood that they could succeed. These two estimates of potential DA IRP cost reduction (payoff and probability-weighted payoff) were used to determine a preferred and a backup technology category for each remedial action category and to prioritize the categories for the entire set of DA IRP activities considered.

The resulting prioritized or ranked set of technology categories was used to develop preferred R&D strategies for four levels of R&D funding, ranging from current funding to 300% of current funding. It was assumed, based on USATHAMA experience to date, that currently projected R&D funding for the period from 1991 through 1995 would allow development in four technology categories (physical, biological, chemical, and thermal) and that if R&D funding increased, more technology categories could be developed. (For this study funding increases in increments of current level funding, current funding +50%, current funding +100%, and current funding +200% were used to evaluate what new technology categories could be developed funding increased.) This assumption is only a first approximation, and the required

funding for any particular set of technology development activities would require more detailed estimates based on the specific activities involved.

Table 2.5 shows the resulting R&D strategies based on these assumptions for the current, 150% (50% additional funding), 200% (another 50% additional funding), and 300% (another 100% additional funding) funding levels. Also shown in Table 2.5 are two measures of the potential payoff for each of these R&D investment strategies. The incremental expected payoff for each incremental R&D investment is expressed as a ratio of the estimated expected DA IRP cost savings and the assumed investment of R&D funding. The incremental potential payoff is the ratio of the maximum estimated savings and the R&D investment. The development of these R&D strategies and the estimated payoffs is discussed in Section 6.

Table 2.5 indicates that an expected or typical payoff for investing in the four technology categories with the highest priority would range from 3:1 to 20:1 (DA IRP cost reduction 3 to 20 times larger than R&D investment), and could be as high as 100:1. As would be anticipated, as R&D investment in lower priority technology categories is projected, the estimated expected and potential payoffs shown in Table 2.5 both decrease accordingly. Based on the estimates in the table, doubling current R&D funding to allow development of technologies from four additional technology categories appears to be a cost-effective investment. The return on these investments would be lower than for the higher priority technology categories, but still sufficiently high to warrant consideration. The set of eight technology categories identified for this funding level consists of the preferred technology category for each remedial action category, plus backup technologies for EXPs-contaminated soil and groundwater remedial actions.

The mix and order of priority for technology categories for the 200% funding level seems reasonable based on an intuitive assessment of potential DA IRP requirements. Based on the partial estimate of soil remedial actions shown in Table 2.1, it seems likely that costs associated with EXPs-contaminated soil will be a large fraction of DA IRP soil remedial action costs. Therefore, it seems reasonable to invest in two technology categories to enhance the probability that DA IRP cost is reduced, and it is not

TABLE 2.5. R&D Investment Strategies and Payoffs (Savings:Investment) by Funding Level Increments

Funding Level	Technology Categories	Incremental Probability-Weighted Payoff	Incremental Potential Payoff[a]
Current Funding	In Situ Biological Technology for VOCs-Contaminated Groundwater Biological Technology for EXPs-Contaminated Soil In Situ Biological Technology for EXPs-Contaminated Groundwater Chemical Technology for EXPs-Contaminated Soil	3:1 to 20:1	100:1
+ 50%	Onsite Physical Technology for EXPs-Contaminated Groundwater Onsite Chemical Technology for HMs-Contaminated Groundwater	1:1 to 10:1	20:1
+ 50%	Physical Technology for HMs-Contaminated Soil Biological Technology for VOCs-Contaminated Soil	1:1 to 3:1	10:1
+ 100%	Onsite Biological Technology for HMs-Contaminated Groundwater Onsite Biological Technology for VOCs-Contaminated Groundwater Thermal Technology for VOCs-Contaminated Soil Thermal Technology for HMs-Contaminated Soil	<1:1 to 3:1	none

(a) Estimated maximum payoff for current funding level and for increasing funding increments.

surprising that investment in a second technology for this remedial action category is a higher priority than investing in a technology for reducing remedial actions involving soil contaminated with HMs and VOCs.

The mix and order of priorities for developing groundwater remedial action technology categories is also intuitively consistent. According to the estimated volumes of contaminated groundwater shown in Table 2.2, the category with the largest potential requirement for treatment is groundwater contaminated with VOCs. This large potential requirement results in a high priority and a high potential payoff for developing an in situ biological technology. The payoff for a backup technology (onsite biological technology) is substantially lower because extraction of the groundwater from the aquifer would still be required, and the unit cost for the reference treatment technology (air stripping and vapor-phase carbon treatment) is relatively low. In addition, the likelihood of achieving this lower payoff is judged to be low.

The estimated payoff and priority for developing an in situ biological technology for groundwater contaminated with EXPs is slightly lower than that for in situ biological technology for groundwater contaminated with VOCs, based on the lower estimated amount of contaminated water needing treatment. However, the estimated payoff for developing a backup onsite physical technology for explosives-contaminated groundwater is slightly higher than the estimated payoff for developing a backup technology for groundwater contaminated with VOCs, and the estimated probability for successfully developing an onsite physical technology for groundwater contaminated with EXPs was assessed as medium. Therefore, a backup technology for EXPs-contaminated groundwater has a higher priority than one for VOCs-contaminated groundwater.

The last four technologies in Table 2.5 that could be developed if R&D funding were available are all backup technologies, and therefore do not increase the potential savings that could be realized. Rather, they can be considered insurance. Investing in these technologies would increase the overall likelihood of reducing costs for their respective DA IRP remedial action categories. However, since the potential payoffs are smaller for these remedial action categories, the overall impact of investing in these technologies on the expected DA IRP cost savings is relatively small. Estimates of the expected payoffs for this last increment of R&D funding ranged from less than 1 (R&D investment not recovered) to 3:1 (DA IRP cost reduction three times as large as the R&D investment).

3.0 CONTAMINATED SOIL REMEDIAL ACTIONS

This section of the report describes the results of the analysis that was performed to determine target unit costs of alternative technologies for remedial actions involving soils contaminated with EXPs, HMs, and VOCs. Also described are the corresponding estimated savings for the DA IRP if those target costs can be achie\ J. The estimated savings, or payoff, for developing an alternative technology that achieves the target unit cost is one of the factors that is considered in Section 6 for determining R&D investment priorities.

Section 3.1 summarizes the estimates made of the volume of soils contaminated with EXPs, HMs, and VOCs for that portion of the potential sources for which available data are identified. Though these volume estimates are not comprehensive and are based on preliminary installation characterization data, they provide a sufficient basis for making a first-order estimate of the amount of soil to be treated in each category. These estimates are necessary for comparing potential IRP cost reductions even though potential cost reductions could be larger.

Section 3.2 identifies the current reference technology assumed for each category of soil remedial action and presents a unit cost estimate for those technologies. These unit cost estimates are used in Section 3.3 as the basis for determining target unit costs for alternative technologies for remedial actions involving EXPs, HMs, and VOCs. The payoffs or savings associated with achieving those unit cost targets are also estimated in Section 3.3.

Throughout this section, data and results are presented in terms of fairly broad ranges, and the supporting calculations make liberal use of rounding and approximating. Additional precision is unwarranted by the nature of the data that are available for estimating how much contaminated soil must be treated.

3.1 ESTIMATES OF CONTAMINATED SOIL VOLUME

The estimated volumes of soils contaminated with EXPs, HMs, and VOCs are presented in this section. The objective of estimating the volumes of these

soils at Army installations is to develop a relative measure of the Army's soil remedial action requirements. The order-of-magnitude contaminated soil volumes are used with cost data to estimate potential cost reductions from successful R&D activities.

Soil volumes were estimated by calculating the volume of contaminated soil at a subset of the Army's installations for which preliminary data are available and by assuming that these volumes represent a lower limit estimate of the total contaminated soil volumes. The subset of Army installations used in this study included those involved in munitions production, plating and metal finishing, and other industrial operations (e.g., equipment maintenance). These installations probably generate a large fraction of the Army's contaminated soil. Therefore, it is reasonable to consider data for these installations to be representative of the Army soil remedial action requirements.

Two reports were examined as sources for estimating contaminated soil volumes: one by Roy F. Weston, Inc. (WESTON) (Coia et al. 1983), and another by Environmental Science and Engineering, Inc. (Beaudet et al. 1983a,b,c). The WESTON report was used as the primary source of information for this study. In that report, WESTON surveyed 41 installations associated with munitions production, plating and metal finishing, and other industrial operations (i.e., equipment maintenance) for the use of wastewater lagoons. Thirty-nine of those installations had some combination of wastewater lagoons contaminated with EXPs, HMs, and VOCs. Wastewater lagoons are considered the greatest known source of contaminated soil. Other sources include burning grounds and the soil around production facilities. Sources of available data to estimate the extent of the contamination associated with burning grounds and production facilities were not identified.

A summary of the estimated contaminated soil volumes is presented in Table 3.1 and Figures 3.1 and 3.2. Details of the soil volume calculations used for the estimates presented in Table 3.1 and in the two figures can be found in Appendix A. The soil volume calculations were based on an assumed depth of contaminated soil around the wastewater lagoons. The actual depth

TABLE 3.1. Relative Measure of the Contaminated Soil at Army Installations (Estimated from Data Currently Available)

	Contamination Category		
	Explosives	Heavy Metals	Volatile Organics
Number of Installations Identified from Data Examined as Having Contaminated Soil	28	14	8
Estimated Volume of Contaminated Soil (tons)			
Lagoons, Ditches, Trenches, or Impoundments	~1,000,000	~210,000	~180,000
Burning Grounds	?	?	?
Area Around Facilities	?	?	?
Other Installations	?	?	?
TOTAL (±20%)	>1,000,000	>210,000	>180,000

of contaminated soil that must be treated at each site will be negotiated with the appropriate regulatory agencies and is unknown at this time. Therefore, a range of ±20% was included in the estimate of the contaminated soil volumes.

Table 3.1 summarizes the number of installations (from among those for which data are available) and the potential volume of contaminated soil at those installations for each contamination category. As noted above, wastewater lagoons are not the only source of contaminated soil; therefore, the totals presented in the table represent the lower limits of the total volumes of IRP contaminated soil. As shown in Table 3.1, it is estimated that there will be about five times as much soil contaminated with EXPs (at the installations surveyed) as soil contaminated with HMs and VOCs.

The number of installations with contaminated soil volumes more than and less than 20,000 tons for each contamination category is presented in Figure 3.1. Figure 3.2 plots the contribution to the total soil volume of the installations with less than 20,000 tons for each contaminant type. The data presented in Figures 3.1 and 3.2 indicate that installations with "small" volumes (less than 20,000 tons) of contaminated soil, although they are large

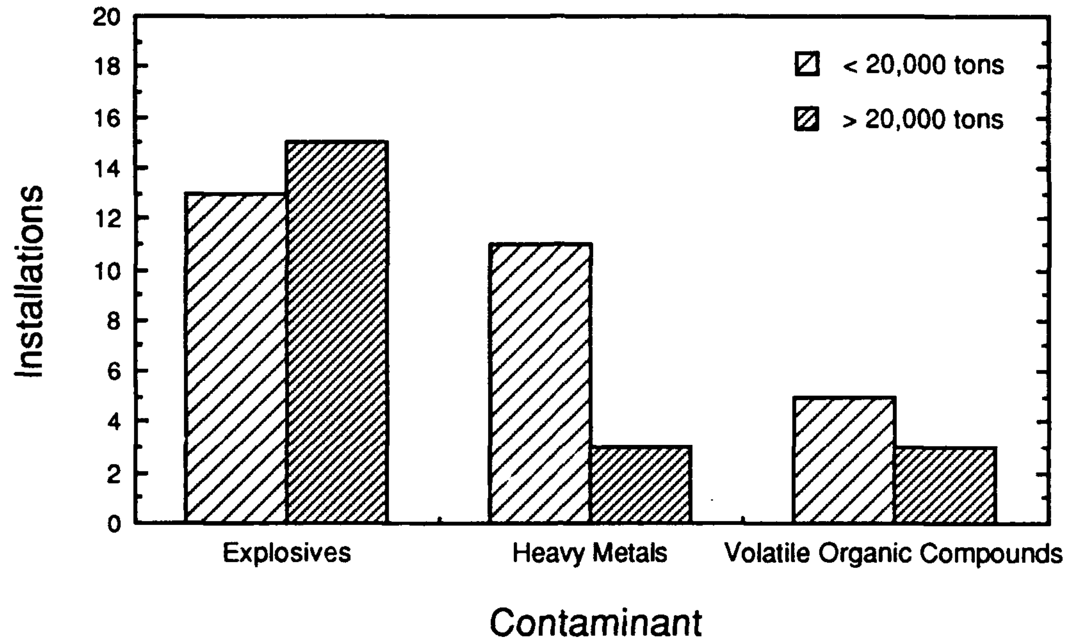

FIGURE 3.1. Number of Installations with More and Less Than 20,000 Tons of Contaminated Soil

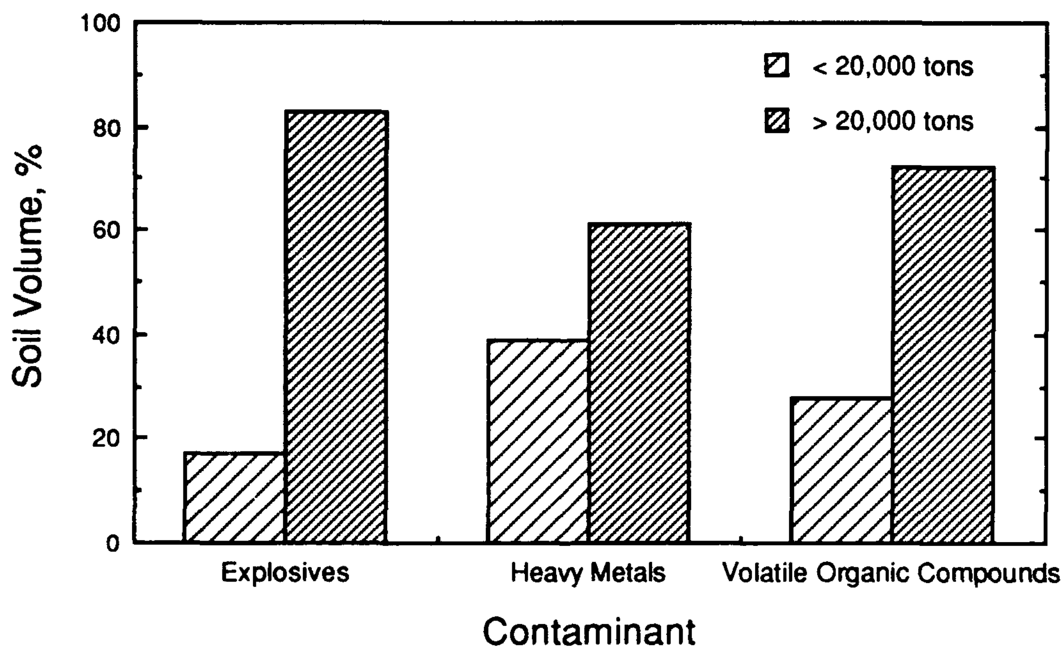

FIGURE 3.2. Contribution to Total Soil Volume

in number, contribute a small percentage of the total soil volume. For EXPs contamination, installations with small volumes of contaminated soil contribute less than 20% of the total volume of soil. For HMs and VOCs contamination, total contribution from small sites is less than 40% and 30%, respectively.

3.2 UNIT COST ESTIMATES FOR REFERENCE SOIL REMEDIAL ACTION TECHNOLOGIES

This section describes the cost data and assumptions that were used to develop estimates of the unit costs for the reference remedial action technologies for each of the soil contamination categories. The resulting unit costs are used in Section 3.3 as the bases for developing target unit costs for developmental technologies and for estimating the corresponding DA IRP cost savings if those targets can be realized through R&D of alternative remedial action technologies.

Sections 3.2.1, 3.2.2, and 3.2.3 describe the cost data, assumptions, and unit costs for the reference soil remedial action technologies for soil contaminated with EXPs, HMs, and VOCs, respectively. The unit costs for remedial actions associated with these contaminant categories are expressed in terms of dollars per ton of contaminated soil; they include the costs associated with removal of the contaminated soil, subsequent treatment, and disposal of secondary wastes and/or decontaminated soil. The unit cost for each contamination category is a function of the assumed reference technology and of the amount of soil that is assumed to be treated at each installation.

3.2.1 Unit Cost for Remedial Actions Involving Soils Contaminated with Explosives

The reference remedial action technology for soils contaminated with EXPs is incineration, which involves excavation of the soil followed by incineration in a rotary kiln incinerator and disposal of the ash at the excavation site. As part of the DA IRP, USATHAMA has completed incineration of approximately 40,000 tons of EXPs-contaminated soil at Cornhusker Army Ammunition Plant (CAAP) and initiated incineration of an estimated 120,000 tons of soil at Louisiana Army Ammunition Plant (LAAP) (Turkeltaub and Wiehl 1988).

The major cost components associated with incinerating EXPs-contaminated soil are 1) excavation, 2) mobilization and demobilization of the incineration process equipment, 3) incineration processing cost, and 4) disposal of the ash from the incineration process. For the purposes of this study, the costs associated with these activities at LAAP were used as a basis for estimating the unit costs for incinerating soils contaminated with EXPs at other installations. The resulting unit cost estimates should be considered approximations, because costs for incineration at other installations will depend on the specific characteristics of the contaminated soil and the type of contract negotiated for incineration. It should also be noted that these incineration unit cost estimates do not include other costs such as site preparation and management costs and are therefore not appropriate as estimates of the total cost for an incineration campaign. These other costs were not included because they have relatively little effect on comparisons between the cost of using the reference or potential developmental technologies.

Table 3.2 gives the estimated unit or total costs for the four incineration cost components for the LAAP incineration effort. The data in the table were provided by USATHAMA and are based on the estimated costs for incinerating 120,000 tons of soil contaminated with EXPs.

The estimate for excavation and sampling costs is higher than typical remedial action excavation costs, which are on the order of $20/ton, because of the requirements for remote excavation of soils contaminated with EXPs. The requirement for such excavation at other installations with contaminated soil will depend on specific installation conditions.

TABLE 3.2. Estimated Incineration Costs for Explosives-Contaminated Soil at LAAP

Cost Component	Cost
Excavation and Sampling	~$40/ton
Mobilization and Demobilization	$4.2 million
Incineration	~$110/ton
Ash Disposal	~$10/ton

The incineration at LAAP is being performed by the International Technology (IT) Corporation of Knoxville, Tennessee, using their hybrid thermal treatment system (HTTS). The HTTS is a rotary kiln capable of incinerating up to 26 tons per hour of soil contaminated with EXPs (Turkeltaub and Wiehl 1989). The cost data shown on Table 3.2 for mobilizing, demobilizing, and operating this incinerator were provided by USATHAMA based on the terms of their contract with IT for performing these activities. The cost of ash disposal shown on Table 3.2 was also provided by USATHAMA and is also based on the terms of their contract for the performance of this activity at LAAP. The estimated cost is based on the assumption that the ash from the incinerator is hauled to the excavation site, compacted, and covered with a berm.

Figure 3.3 shows how the unit cost for incineration of soil contaminated with EXPs would vary as the amount of contaminated soil varies, assuming that the excavation, mobilization and demobilization, incineration, and ash disposal costs at other installations were similar to those at LAAP. The estimated unit cost shown in Figure 3.3 varies with the amount of soil incinerated because the mobilization and demobilization cost is averaged over different amounts of soils.

The incineration unit cost shown in Figure 3.3 is likely to be a reasonable estimate for incineration costs at an installation for which the assumed incineration equipment is appropriate. However, the HTTS, which has a very large throughput capacity (26 tons per hour), may be oversized for installations with relatively small incineration requirements. The problem with an oversized incinerator is illustrated in Figure 3.3 by the very high unit costs that would result from using such equipment at installations with 10,000 to 20,000 tons of soil contaminated with EXPs.

Figure 3.3 also shows the unit costs of using a smaller scale incinerator. It is assumed that excavation and ash disposal costs would be the same for the smaller incinerator, but mobilization and demobilization and incineration costs would be different. The mobilization and demobilization and incineration costs used for estimating the smaller incinerator's unit cost are based on cost data for a 5-ton-per-hour incinerator operated by the Environmental Systems Company (ENSCO) of Little Rock, Arkansas, at an

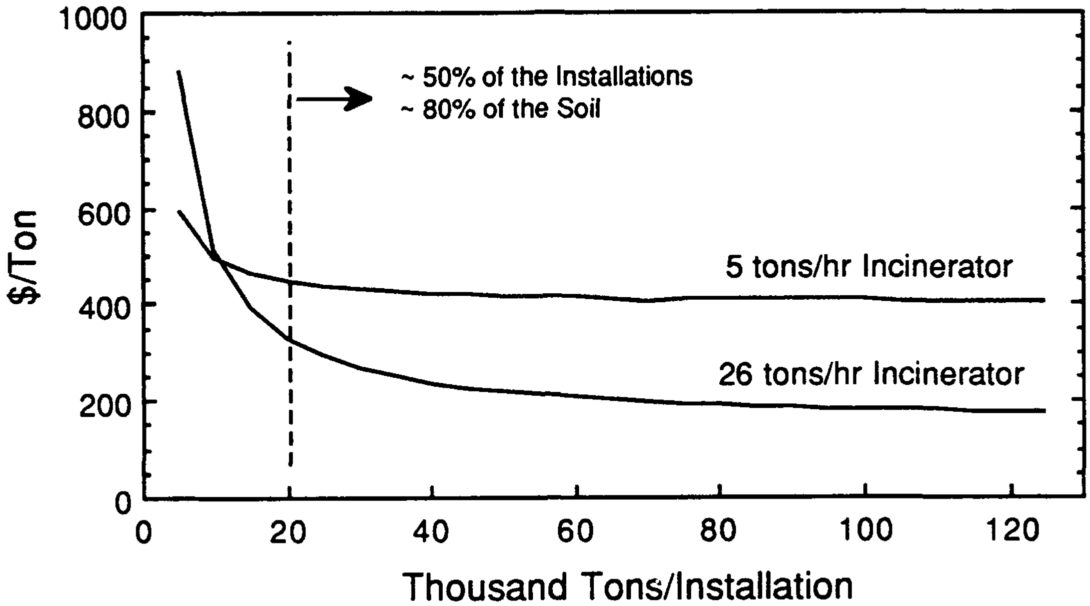

FIGURE 3.3. Estimated Unit Treatment Costs for Soil Contaminated with Explosives from Wastewater Lagoons

oil- and solvent-contaminated site (Frank et al. 1987). The mobilization cost for this incinerator was approximately $1 million, which is substantially lower than the mobilization cost for the HTTS, but the incineration cost was approximately $375/ton, which was substantially higher.

Figure 3.3 shows that the smaller incinerator would have a lower unit cost for installations with less than about 10,000 tons of soil contaminated with EXPs. Although some caution should be exercised in comparing these estimates since different contaminants were present, it is likely that the unit incineration cost for smaller amounts of soil is lower than the costs that would result if the larger incinerator were used.

In order to determine the unit cost targets for alternative remedial action technologies for soils contaminated with EXPs and to estimate the corresponding IRP savings that would be realized, two ranges of costs were considered based on the information in Figure 3.3. For installations with less than 20,000 tons of contaminated soil, a range of $300 to $600/ton was

assumed as the unit cost for the reference technology. For installations with larger volumes of contaminated soil, a range of $200 to $300/ton was assumed.

3.2.2 Unit Cost for Remedial Actions Involving Soil Contaminated with Heavy Metals

The reference remedial action technology for soils contaminated with HMs is offsite disposal. For this technology, it is assumed that following its excavation, the contaminated soil is transported offsite to an appropriate RCRA-permitted disposal facility. The implementation of such disposal must be consistent with the Land Disposal Restrictions (LDRs) under the Hazardous and Solid Waste Amendments of 1984 (HSWA). Land disposal of untreated wastes that are categorized as hazardous based on the characteristics of ignitability, corrosivity, or reactivity or based on extraction procedure (EP) toxicity will be prohibited after May 8, 1990. Soils contaminated with HMs fall into this category.

The major cost components associated with offsite disposal of soils contaminated with HMs are 1) excavation, 2) transportation, and 3) offsite disposal. The unit costs estimated for these cost components are shown on Table 3.3. As previously noted, these unit costs do not include such costs as site preparation and management costs, which do not affect the comparison between the reference and alternative technologies.

The excavation and sampling cost estimate is based on calculations using the Cost of Remedial Action (CORA) model developed by CH2M Hill for the U.S. Environmental Protection Agency (EPA) (EPA 1988). The CORA model was developed to estimate remedial action costs from general information that is available before data from the Remedial Investigation/Feasibility Study

TABLE 3.3. Estimated Offsite Disposal Costs for Soil Contaminated with Heavy Metal

Cost Component	Cost
Excavation and Sampling	~$20/ton
Transportation	~$90 to $110/ton
Disposal at Offsite RCRA Disposal Site	~$185 to $205/ton

(RI/FS) report are available; it is used by the EPA and other government agencies for budget estimating. The estimate of $20/ton is a typical unit cost calculated by the CORA model for a variety of assumed soil types and excavation amounts.

The estimated unit transportation cost of $90 to $110/ton is also based on CORA model results. An average distance of 400 to 500 miles from the Army installation to a RCRA disposal site is assumed, based on the locations of the Army installations currently identified as having soils contaminated with HMs (Appendix A) and the locations of existing RCRA disposal sites.

As noted above, the disposal of HMs-contaminated soil must be consistent with the LDRs under the HSWA. EPA has issued proposed guidance levels for soil or debris with inorganic contamination. These guidance levels identify extract concentrations below which treatment is not required prior to disposal and residual extract concentrations that must be achieved as a result of treatment in order to dispose of such wastes at a RCRA disposal site (Offutt 1988). This analysis assumes that soil sufficiently contaminated with HMs to require removal would require treatment prior to disposal.

The offsite disposal component unit cost shown on Table 3.3 is the fee assessed for disposing of the contaminated soil at a RCRA-permitted landfill. As noted above, treatment of the contaminated soil is assumed to be required prior to its disposal. It is also assumed that the soil is treated at the RCRA landfill site prior to disposal and that treatment costs are included in the disposal fee. This analysis also assumes that the fee for disposing of the contaminated soil is the final cost incurred by the Army. No allowance is made for any subsequent cost that the Army might incur for future cleanup activities at the landfills.

Four landfill operators in different parts of the country were contacted to determine typical rates for disposal only and disposal plus treatment for soil contaminated with HMs. The quoted rates ranged from $85 to $130/ton for disposal of bulk soil and $185 to $205/ton for treatment and disposal. The CORA model indicates that a typical fee for disposal only would be $120/ton. The rates quoted for treatment and disposal seem to be typical or representative rates because there is good agreement between the quoted rates for

disposal only and the value used in the CORA model; therefore, a fee of \$200/ton was assumed for treatment and disposal.

Based on the component unit cost estimates on Table 3.3, a unit cost of \$300 to \$340/ton (rounded) is used in Section 3.3 as a basis for determining a unit cost target for alternative technology. Unit costs for alternative technologies are compared with this range of unit costs for the reference HMs soil remedial action technology to estimate the potential IRP cost savings if the alternative technologies can be successfully developed.

3.2.3 Unit Cost for Remedial Actions Involving Soil Contaminated with Volatile Organic Compounds

The reference remedial action technologies for soils contaminated with VOCs are in situ volatilization and low-temperature thermal stripping (LTTS). In situ volatilization technology has been employed since early 1986 at two sites at the Twin Cities Army Ammunition Plant (TCAAP) at New Brighton, Minnesota, and has been used to remove over 160,000 pounds of volatiles from these sites (Oster et al. 1988). However, in situ volatilization requires specific site characteristics and conditions to allow the vacuum extraction process to remove a sufficient portion of VOCs to meet cleanup objectives, and it may not be a technically viable option for general application.

Because of the limitations of in situ volatilization, USATHAMA has developed and is demonstrating LTTS as an alternative technology. The LTTS process involves heating the contaminated soil to approximately 400°F via an indirect heat exchanger to strip the moisture and VOCs from the soil. The organic vapors are then processed by condensation and an afterburner or fume incinerator independent of the soil matrix (Nielson et al. 1988). Scrubbing of HCl vapors will normally be required as part of this process. For the purposes of this study, LTTS is assumed to be the reference technology, since it can be applied under most site conditions.

The major cost components associated with LTTS of soil contaminated with VOCs are 1) excavation, 2) mobilization and demobilization of the LTTS process equipment, 3) LTTS processing cost, and 4) disposal of the treated soil from the LTTS process. The unit costs for these components are shown in Table B.3. As previously noted, these unit costs do not include such costs

as site preparation and management costs, which do not affect the comparison between the reference and alternative technologies.

The excavation and sampling cost estimate is based on calculations using the CORA model. The estimate of $20/ton is a typical unit cost calculated by the CORA model for a variety of assumed soil types and excavation amounts.

The unit costs shown on Table 3.4 for thermal stripping were provided by USATHAMA and are based on recent estimates provided by WESTON. WESTON has developed and demonstrated the LTTS technology under contract with USATHAMA and has received a patent for the process. This study assumes that scrubbing will generally be required to meet emission standards, and the unit costs with and without scrubbing are used to determine appropriate unit cost targets for alternative developmental technologies.

The unit cost for disposal of treated soil shown on Table 3.4 is the same as the assumed cost for disposing of ash from incineration, and it is also based on the LAAP cost estimate for this operation. It is assumed that the treated soil from the LTTS process would also be returned to the extraction site, compacted, and covered with a berm.

Figure 3.4 shows how the unit cost for LTTS of soils contaminated with VOCs would vary as the amount of contaminated soil varies. The estimated unit cost shown on the figure varies slightly with the amount treated because the mobilization and demobilization cost is levelized over different amounts of soil. The unit cost shown on Figure 3.4 is used in Section 3.3 as a basis for determining a unit cost target for an alternative technology. Unit costs for alternative technologies were compared with a unit cost range of $170 to

TABLE 3.4. Estimated Low Temperature Thermal Stripping Costs for Soil Contaminated with Volatile Organic Compounds

Cost Component	Cost
Excavation and Sampling	~$20/ton
Mobilization and Demobilization	~$85,000
LTTS (without scrubber)	~$120/ton
LTTS (with scrubber)	~$140/ton
Treated Soil Disposal	~$10/ton

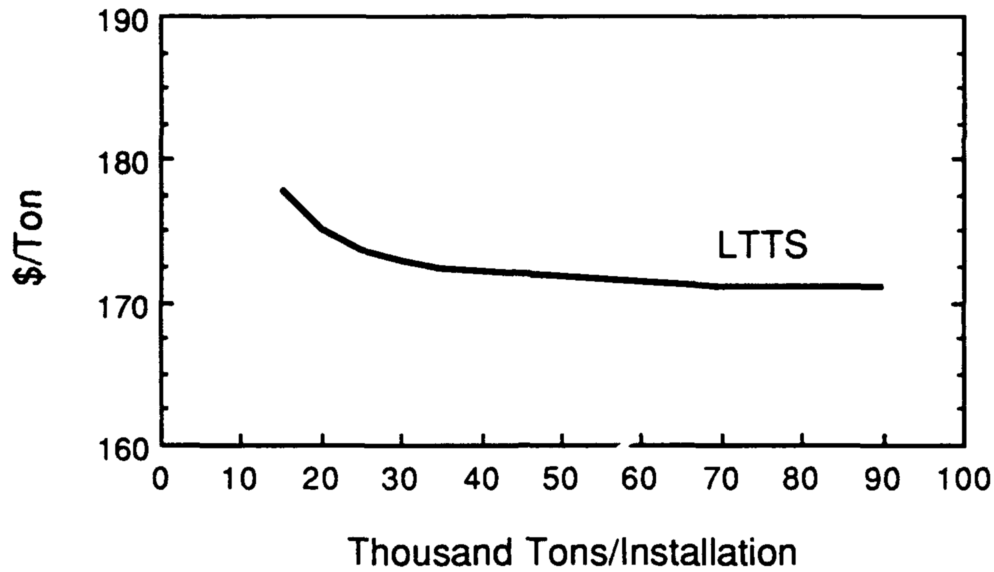

FIGURE 3.4. Estimated Unit Treatment Costs for Soil Contaminated with Volatile Organic Compounds from Wastewater Lagoons

$180/ton for LTTS to estimate the potential IRP cost savings if the alternative technologies can be successfully developed.

3.3 UNIT COST TARGETS AND PAYOFFS FOR ALTERNATIVE TECHNOLOGIES FOR SOIL REMEDIAL ACTIONS

This section describes the unit cost targets for alternative soil remedial action technologies, which are used in Section 5 as one of the bases for assessing categories of alternative soil remedial action technology. The corresponding payoff, in terms of IRP cost savings if those developmental targets can be achieved, is also discussed. These estimates for potential savings are used in Section 6 as a factor in determining priorities among alternative R&D investments.

Unit cost targets were selected in one of two ways. For some technology categories, USATHAMA has previously established unit cost targets for developmental technologies. Those targets were adopted for use in this report. When no target had been previously determined, a target unit cost was selected that was low enough, relative to the reference technology unit cost, to

result in a significant IRP cost savings, relative to the reference cost, for the remedial action activity. However, some judgment was necessary to avoid establishing unit cost targets that are so low they are unrealistic or unachievable based on current expectations for alternative technologies.

Three major uncertainties make estimating potential savings for successfully developing alternative technologies difficult. There are large uncertainties in the amount of remedial action that will be required for those Army installations for which data are available. Also, the unit cost for the reference technology is uncertain, depending on specific application conditions such as the amount of soil or groundwater to be treated or processed and its degree of contamination. Finally, the amount that would be saved if the developmental technology were applied at other installations or to other wastes at the installations considered is unknown. Because of these uncertainties, broad ranges of potential savings are estimated, and calculations performed make liberal use of rounding and approximation. The current basis for this estimate does not warrant calculational precision.

Sections 3.3.1, 3.3.2, and 3.3.3 describe the developmental technology unit cost targets and the corresponding IRP cost savings for soils contaminated with EXPs, HMs, and VOCs, respectively. Table 3.5 summarizes those unit cost targets and estimated savings. The range of savings for each category shown on the table corresponds to the DA IRP cost reductions for the portion of the total contaminated soil for each category that was considered in Section 3.1. Additional remedial action requirements for contamination from other sources could increase the potential savings that would be realized if the developmental technologies achieve target unit costs.

TABLE 3.5. Unit Cost Targets and Payoffs for Remedial Action Technologies

Soil Contamination Category	Target Unit Cost	Payoff
EXPs	$100/ton	$100 to $300 million
	$50/ton	$150 to $350 million
HMs	$200/ton	$20 to $35 million
	$300/ton	less than $10 million
VOCs	$50/ton	$20 to $30 million

3.3.1 Unit Cost Targets and Payoffs for Remedial Action Technologies Involving Soils Contaminated with Explosives

The reference remedial action for soils contaminated with EXPs is excavation, incineration, and replacement of the ash at the excavation site. Based on the installation data examined in Appendix A and summarized in 3.1, it is estimated that at least 1,000,000 (±20%) tons of contaminated soil will require treatment, 20% of which is at installations with less than 20,000 tons of contaminated soil. The cost estimates developed in Section 3.2.1 for these remedial activities indicate that their unit cost varies with the amount of contaminated soil. For remedial action of less than 20,000 tons, the unit cost varies from about $300 to $600/ton. For larger remedial actions the unit cost varies from about $200 to $300/ton.

USATHAMA has previously established unit cost targets for a biological technology (composting) and a chemical technology (as yet unidentified) for remedial action involving soil contaminated with EXPs. In its development of composting, USATHAMA is attempting to achieve a unit cost on the order of $100/ton. If USATHAMA decides to develop a chemical technology for treatment of soil contaminated with EXPs, they will seek a process that has a unit cost on the order of $50/ton.

If the $100/ton target for composting is achieved, a savings of $200 to $400/ton would be realized for installations with less than 20,000 tons of contaminated soil, and $100 to $200/ton would be saved at installations with more contaminated soil. For the 1,000,000 (±20%) tons of contaminated soil identified from the installation data currently available, approximately $30 to $100 million would be saved at installations with less than 20,000 tons of contaminated soil (150,000 to 250,000 tons @ $200 to $400/ton savings). At installations with larger amounts of contaminated soil, $65 to $190 million would be saved (650,000 to 950,000 tons @ $100 to $200/ton savings). A total savings of about $100 to $300 million would be realized for remedial actions for contaminated soil sources currently identified. Each of these savings would be $50/ton higher if the $50/ton target for chemical treatment of soil

contaminated with EXPs were achieved. Similar calculations indicate that $150 to $350 million would be saved for remedial actions for contaminated soil sources currently identified.

3.3.2 Unit Cost Targets and Payoffs for Remedial Action Technologies Involving Soil Contaminated with Heavy Metals

The reference remedial action technology for soil contaminated with HMs is offsite disposal at a RCRA-permitted landfill. Based on the installation data examined Appendix A and summarized in Section 3.1, disposal of approximately 210,000 (±20%) tons of contaminated soil will be required. The unit cost for such disposal is estimated in Section 3.2.2 to be $300 to $340/ton.

A unit cost target of $200/ton for alternative soil treatment technologies was adopted for this study. This target was selected because it would afford significant potential savings (about one-third of the potential cost for such remedial actions) but is still a reasonable target for potential developmental technologies based on an examination of these potential technologies. If an alternative technology were successfully developed with a unit cost of $200/ton, a savings of $100 to $140/ton could be realized for 170,000 to 250,000 tons (210,000 ± 20%). Approximately $20 to $35 million would be saved for remedial actions for contaminated soil sources currently identified.

For soils contaminated with HMs, a second cost target was considered. It may be preferable to perform remedial actions for these soils onsite even if no cost savings can be currently identified. Offsite disposal of contaminated soil in RCRA-permitted disposal sites may have subsequent unquantifiable costs associated with it. If environmental restoration activities were required at any of the disposal sites used as part of the DA IRP, the Department of the Army could incur subsequent financial liability. If an alternative technology with an equivalent unit cost to offsite disposal (~$300/ton) existed, it would not afford a major cost savings (less than $10 million), but could preclude such liability.

3.3.3 Unit Cost Targets and Payoffs for Remedial Action Technologies Involving Soil Contaminated with Volatile Organic Compounds

For the purposes of considering unit cost targets for developmental technologies, the reference technology for treating soil contaminated with VOCs is LTTS. Based on the installation data examined in Appendix A and summarized in Section 3.1, disposal of approximately 180,000 (±20%) tons of contaminated soil will be required. The unit cost for such disposal is estimated in Section 3.2.3 to be $170 to $180/ton.

USATHAMA has previously adopted a target of $50/ton for in situ biological treatment of soil contaminated with VOCs. If this target can be achieved, a savings of $120 to $130 per ton can be realized for 140,000 to 220,000 tons of contaminated soil (180,000 ± 20%). On the order of $20 to $30 million would be saved for remedial actions for contaminated soil sources currently identified.

4.0 CONTAMINATED GROUNDWATER REMEDIAL ACTIONS

The results of the analysis that was performed to determine target unit costs for alternative remedial action technologies involving groundwater contaminated with EXPs, HMs, and VOCs are described in this section. Also described are the corresponding estimated savings for the DA IRP if those target costs can be achieved. The estimated savings, or payoff, for developing an alternative technology that achieves the target unit cost is one of the factors that is considered in Section 6 for determining R&D investment priorities.

Section 4.1 summarizes the estimates made of the volume of groundwater contaminated with EXPs, HMs, and VOCs for that portion of the potential sources for which available data were identified. As previously noted for the contaminated soil volume estimates, the estimates of contaminated groundwater are not comprehensive and have large uncertainties because they are based on preliminary installation characterization data. However, the estimates do provide a sufficient basis for making a first order assessment of the amount of groundwater to be treated in each category, which is necessary to approximate potential DA IRP groundwater remedial action cost reductions.

Section 4.2 identifies the current reference technologies assumed for each category of groundwater remedial action and presents unit cost estimates for those technologies. These unit cost estimates are used in Section 4.3 as the basis for determining target unit costs of alternative remedial action technologies for groundwater. The payoff, or savings associated with achieving those unit cost targets, is also estimated in Section 4.3.

Data and results in this section are presented as fairly broad ranges, and the supporting calculations make liberal use of rounding and approximating. Additional precision is unwarranted by the quality of data that are available for estimating how much contaminated groundwater must be treated or for estimating the cost of corresponding remedial actions.

4.1 ESTIMATES OF CONTAMINATED GROUNDWATER VOLUME

The estimated volumes of groundwater contaminated with EXPs, HMs, and VOCs are presented in this section. These estimates were made by determining the number of installations with groundwater contamination and the type of contamination at those installations and by assuming a treatment rate and treatment time for each type of contamination. These estimates were developed for the same subset of installations discussed in Section 3. As in Section 3, the relative volumes of each category of contamination for this subset of installations were assumed to reflect the relative volumes for all the Army installations. In addition, the bases for the parameters needed to develop unit cost estimates (treatment rates, treatment times, and contaminant concentrations) are presented in this section.

The data for estimating the number of installations with groundwater contamination and the type of contamination at each installation were drawn from two reports: the Defense Environmental Restoration Program Annual Report to Congress (DERA 1988) and the Draft IRP Status Report - 31 July 1988 (Anderson 1988). These reports indicate that for the 39 installations used to estimate the volumes of contaminated soil, 16 may have groundwater contaminated with EXPs, 7 may have groundwater contaminated with HMs, and 9 may have groundwater contaminated with VOCs. Of the 16 installations identified that may have groundwater contaminated with EXPS, 12 have only EXPs contamination, 2 have EXPs and HMs contamination, 1 has EXPs and VOCs contamination, and 1 has all three types of contamination. There are no installations identified with only groundwater contaminated with HMs. Of the nine installations identified that may have groundwater contaminated with VOCs, three have only VOCs contamination, four have VOCs and HMs, and the remaining two were accounted for above. Figure 4.1 summarizes these data.

Estimates for the following parameters were required to develop the unit costs for the treatment technologies currently identified by USATHAMA: 1) treatment rates, 2) treatment times, and 3) concentration of contaminants. Sections 4.1.1 through 4.1.3 discuss the bases for estimating these parameters. A summary of the estimated values of each parameter is presented in Table 4.1.

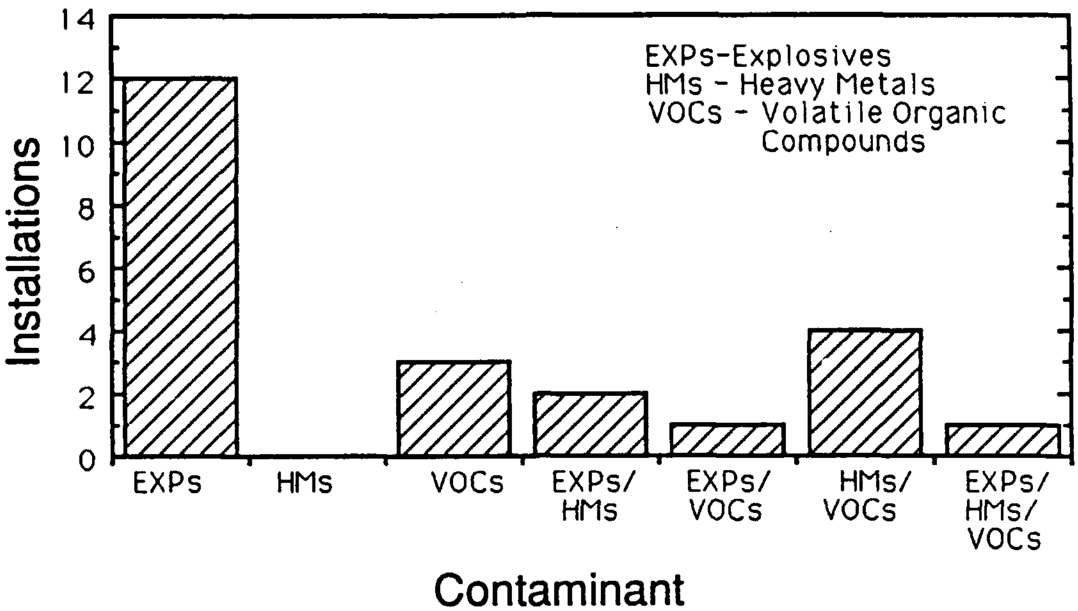

FIGURE 4.1. Number of installations with Groundwater Contamination

4.1.1 Treatment Rates

This section discusses the bases for the treatment rates presented in Table 4.1. The range of treatment rates for groundwater contaminated with VOCs was based on actual data from several Army installations: TCAAP, Anniston Ammunition Depot (AD), and Sharpe AD. TCAAP is currently treating groundwater contaminated with VOCs at a rate of 4 Mgal/day, which is approximately 2800 gpm. Sharpe AD is treating about 183,000 gal/day of groundwater, or approximately 130 gpm. Anniston AD reports treatment rates of about 300,000 gal/day or 210 gpm. Using these data as a basis, a range of treatment rates (100 to 3000 gpm) was used in subsequent calculations.

The Army has not yet treated groundwater contaminated with EXPs; therefore, actual data on which to base treatment rates do not exist. The range of treatment rates presented in Table 4.1 for EXPs in groundwater was based on simple hydrogeological calculations using adsorptivity coefficients of TNT, RDX, and tetryl and using assumptions about the geology of a typical aquifer. The estimated treatment rates (100 to 400 gpm) seem reasonable since EXPs contamination in an aquifer is expected to spread significantly

TABLE 4.1. Relative Measure of Contaminated Groundwater at Army Installations

	Contamination Category		
	Explosives	Heavy Metals	Volatile Organics
Number of Installations Currently Identified from Data Examined as Having Contaminated Groundwater	16	7	9
Assumed Treatment Rate, gpm	100 to 400	100 to 3000	400 to 3000
Assumed Treatment Time, years	20+	20+	20+
Average Concentration, ppm	5 to 15	1	0.2 to 3
Estimated Volume of Contaminated Groundwater Treated, billions of gallons			
Installation/Assumptions Currently Identified	20 to 70	10 to 70	10 to 280
Treatment Beyond 20 Years	?	?	?
Other Installations	?	?	?
TOTAL VOLUME	>20 to 70	>10 to 70	>10 to 280

more slowly than VOCs because of the differences in solubilities and, therefore, adsorptivities of EXPs and VOCs (Lyman 1982; Freeze and Cherry 1979).

The data presented in Figure 4.1 indicate that HMs contamination is typically found in the aquifers in combination with either EXPs or VOCs contamination. USATHAMA is only expecting to treat the effluents which result from treating VOCs and EXPs for HMs if the effluents have HMs concentrations above applicable regulatory standards. Therefore, USATHAMA expects to treat for HMs at the same rate that groundwater contaminated with EXPs and VOCs is being treated (100 to 400 gpm, and 100 to 3000 gpm, respectively).

4.1.2 Treatment Times

A treatment time of 20 years was selected by USATHAMA as a planning base, although longer treatment times are expected. Treatment times are commonly anticipated to be on the order of 30 to 50 years or longer (SAIC 1988:S5-10). Treatment times are primarily dependent on the initial

concentration of the contaminant(s), the adsorptivity of the contaminant(s), the aquifer hydrogeology, and the target concentration. Generally, compounds that are more mobile in the groundwater will have lower treatment times than compounds that are less mobile. VOCs are more mobile than EXPs, and EXPs are more mobile that HMs.

4.1.3 Average Contaminant Concentrations

The assumed concentration of VOCs in groundwater was based on data provided by the TCAAP and Sharpe AD USATHAMA project officers. At the TCAAP, the trichloroethylene (TCE) concentration in the stream averages about 3,000 $\mu g/l$ (3 ppm). At Sharpe AD, the concentrations of TCE, carbon tetrachloride, and dichloroethane are about 200, 4, and 20 $\mu g/l$, respectively. The range of concentrations of EXPs in groundwater was determined by using engineering judgment, and it was substantiated with a simple groundwater model. The HMs concentrations were based on the concentrations of HMs in the wastewater lagoons used by installations involved in plating and metal finishing operations (Coia et al. 1983).

4.2 UNIT COST FOR REFERENCE GROUNDWATER REMEDIAL ACTION TECHNOLOGIES

This section describes the cost data and assumptions that were used to develop estimates of the unit costs for reference remedial action technologies for each of the groundwater contamination categories. The unit costs for remedial actions involving groundwater contaminated with EXPs, HMs, and VOCs are expressed in terms of dollars per 1000 gallons treated. The unit costs discussed in this section include the costs for groundwater extraction, monitoring, discharge of treated groundwater, groundwater treatment, and, where appropriate, costs for managing secondary wastes generated by the treatment process. As with the soil treatment unit costs, costs for site preparation, management, and other costs which do not affect the comparison between the reference and alternative technologies are not included. Sections 4.2.1, 4.2.2, and 4.2.3 discuss the unit costs for remedial actions involving groundwater contaminated with EXPs, HMs, and VOCs, respectively, for the ranges of treatment rates (gpm) described in Section 4.1.

The approach for estimating unit costs for groundwater treatment remedial action technologies differs slightly from that used for estimating the unit costs for the reference soil treatment technologies. There are less data available for estimating the amount of groundwater that must potentially be treated. In addition, there are less actual IRP groundwater treatment cost data than soil treatment cost data available.

Because of these limitations, the CORA cost model was used to estimate all groundwater treatment unit costs. Use of the CORA model provides a consistent basis for estimating all of the groundwater treatment unit cost components for all three contamination categories. This methodology has been evaluated against EPA design, bid, and construction costs for actual remedial actions. The CORA model is currently used by EPA and other government agencies that estimate remedial action costs in order to budget and prioritize (Biggs et al. 1989).

The CORA model estimates capital and first-year operating costs from input data provided by the user relating to the scope of the remedial action. Typical input relates to the size of the remedial action (such as area and depth of contamination, gallons per day treated) and types and concentrations of contaminants. The model uses this information to determine the capital and operating costs for the remedial action, including appropriate contingencies for scope variation and cost uncertainties. These capital and operating cost estimates were used for this study to estimate unit costs for the various groundwater contamination remedial action activities assuming that the remedial actions are performed for 20 years.

4.2.1 Unit Cost for Explosives-Contaminated Groundwater Remedial Actions

The reference remedial action technology for groundwater contaminated with EXPs is granular activated carbon (GAC). GAC requires extraction of the contaminated groundwater from the aquifer. After the groundwater is extracted, it is pumped through beds of carbon granules where organic molecules are selectively adsorbed to the internal pores of the carbon granules. The treated groundwater is then released. In this study, it was assumed that treated water is either reinjected into the aquifer or released to surface water since the disposition of treated water will vary with local conditions

and regulations. It is also assumed that groundwater monitoring is performed concurrently with extraction and treatment to ensure that the treatment mitigates further spread of EXPs contamination in the aquifer.

The major cost components for GAC treatment of groundwater contaminated with EXPs are 1) extraction, 2) GAC treatment, 3) discharge of treated water, and 4) monitoring. The unit cost for each of these components for treatment rates of 100 and 400 gpm (as discussed in Section 4.2) are shown on Table 4.2. The range of unit costs shown on the table for each cost component is based on CORA model calculations. The range of unit costs for each component is the result of variation in the key assumptions used to estimate these costs. These assumptions are discussed below.

For a particular extraction rate, groundwater extraction cost is primarily a function of hydraulic conductivity, which is a measure of the difficulty of transporting water through the soil matrix. A high hydraulic conductivity corresponds to a porous soil matrix through which water is easily pumped, while a low hydraulic conductivity corresponds to a less porous soil matrix such as clay. To estimate the unit cost for groundwater extraction, a range of hydraulic conductivities from 5 ft/day (low hydraulic conductivity) to 50 ft/day (high hydraulic conductivity) was assumed. Other assumptions required to make the CORA model cost estimate were aquifer thickness (25 feet) and average well depth (75 feet). These parameters were selected as "typical" aquifer characteristics and were not varied once it was

TABLE 4.2. CORA Model-Derived Treatment Cost Estimates ($/1000 gal) for Groundwater Contaminated with Explosives

Cost Component	100 gpm	400 gpm
Extraction	$1.00 to $6.00	$1.00 to $6.00
GAC	$3.00 to $4.50	$2.00 to $4.00
Discharge of Treated Water	$0.50 to $2.50	$0.50 to $2.50
Monitoring	$1.50	$0.50
TOTAL	$6.00 to $15.00	$4.00 to $13.00

determined that the CORA model results were not particularly sensitive to their value. The results of a CORA model cost estimate for the range of hydraulic conductivities and extraction rates are shown on Figure 4.2. The figure indicates that the unit cost for groundwater extraction varies from about $1 to $6 per 1000 gallons, depending on hydraulic conductivity, which is the range shown in Table 4.2. The figure indicates that this cost component is not particularly sensitive to the extraction rate, which is reasonable since higher rates can be achieved by introducing more wells with similar capital and operating costs.

Figures 4.3 and 4.4 show the CORA model unit cost estimates for treated water discharge and groundwater monitoring, respectively, for the same range of extraction rates and aquifer characteristics. Figure 4.3 shows that groundwater discharge costs (when treated water is reinjected) vary similarly to extraction costs as hydraulic conductivity is varied. The figure also shows that it is less expensive to discharge the treated groundwater to the surface, as would be expected. The ranges of unit cost for disposal of treated water shown on Table 4.2 correspond to the approximate ranges shown on Figure 4.3 for 100 and 400 gpm.

Figure 4.4 shows the CORA model unit cost estimate for groundwater monitoring costs for the same range of extraction rates. The CORA model monitoring cost estimates are similar for either organic or HMs contamination and are approximately constant (~$0.50/1000 gallons) for extraction rates over 500 gpm. The ranges of unit cost for groundwater monitoring shown on Table 4.2 correspond to the approximate ranges shown on Figure 4.4 for 100 and 400 gpm.

Figure 4.5 shows the range of CORA cost estimates for GAC treatment unit cost for the range of treatment rates and EXPs contamination concentrations discussed in Section 4.1. For the range of treatment rates considered, the estimated unit treatment cost is not very sensitive to treatment rate. However, the estimated unit treatment cost varies by a factor of two for the range of concentrations considered. The ranges of unit costs for GAC treatment of groundwater contaminated with EXPs shown on Table 4.2 correspond to the approximate ranges shown on Figure 4.5 for 100 and 400 gpm.

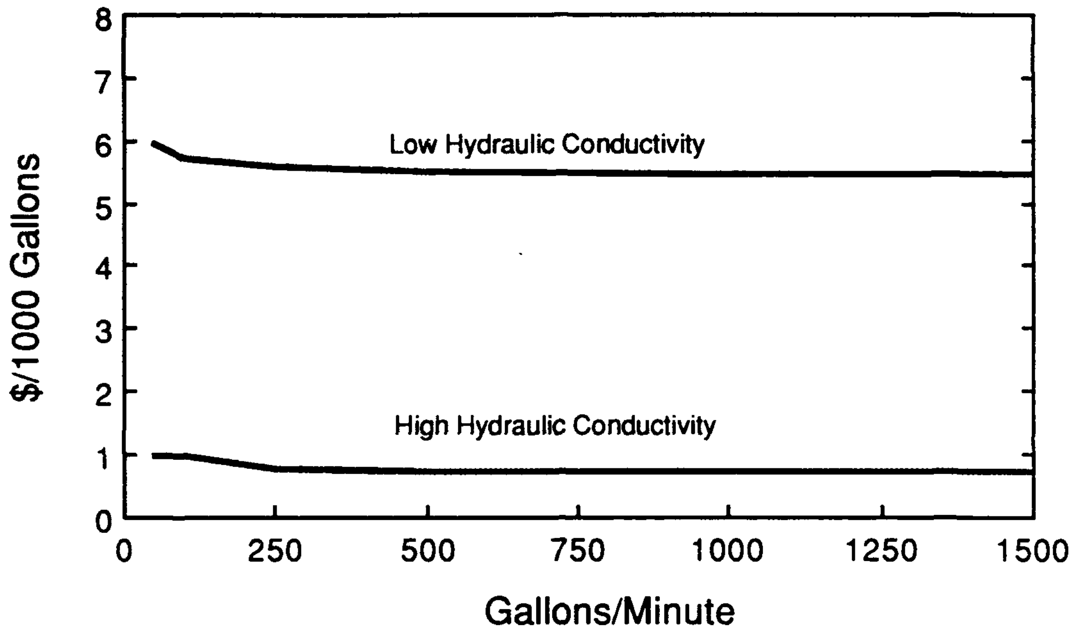

FIGURE 4.2. CORA Model-Derived Unit Cost Estimates for Extraction of Contaminated Groundwater

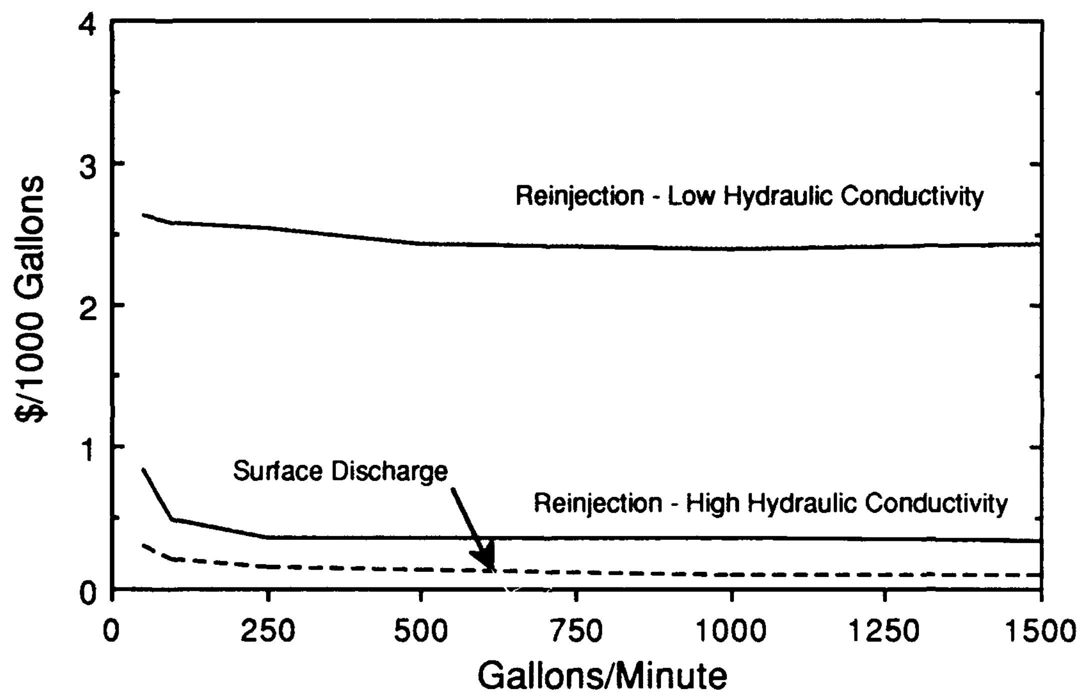

FIGURE 4.3. CORA Model-Derived Unit Cost Estimates for Discharge of Treated Groundwater

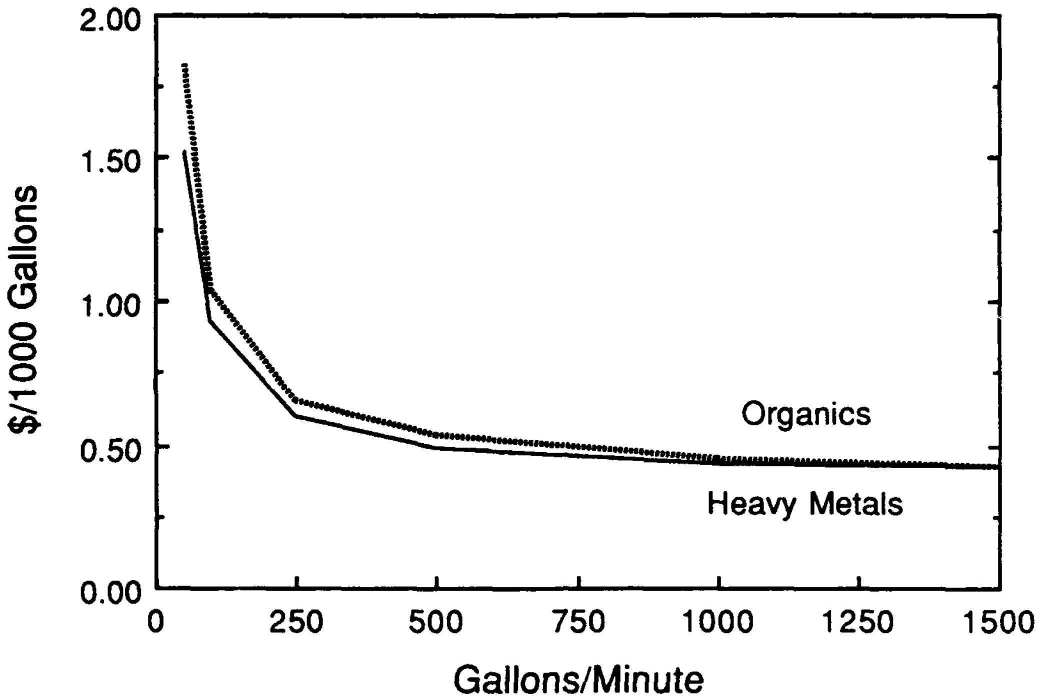

FIGURE 4.4. CORA Model-Derived Unit Cost Estimates for Groundwater Monitoring

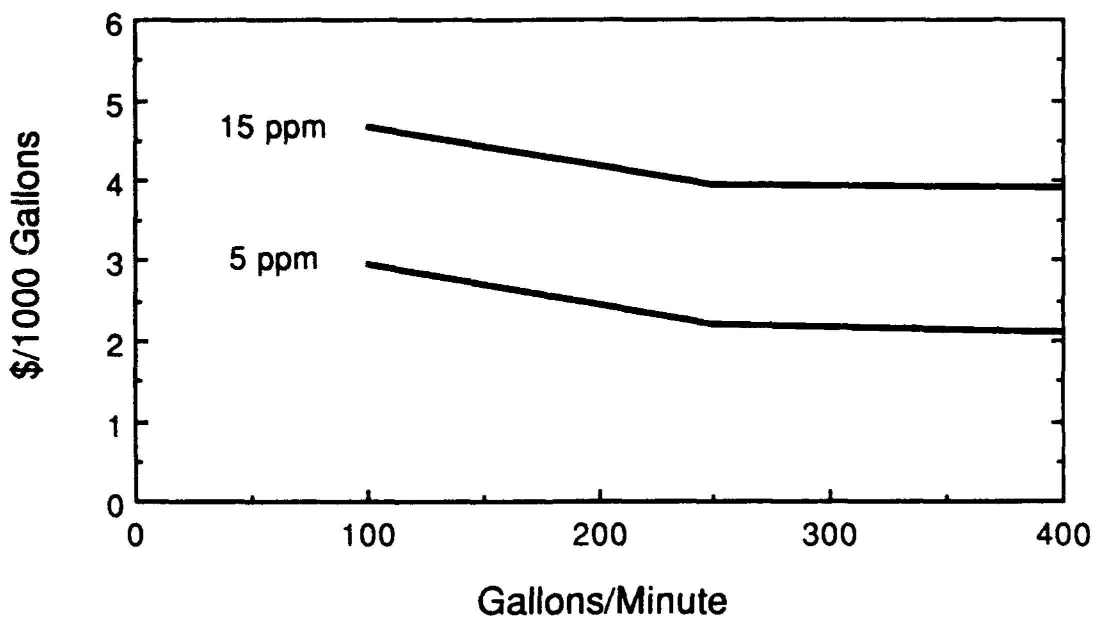

FIGURE 4.5. CORA Model-Derived Unit Cost Estimates for GAC Treatment of Contaminated Groundwater

4.2.2 Unit Cost for Remedial Actions Involving Groundwater Contaminated with Heavy Metals

The reference remedial action technologies for treating groundwater contaminated with HMs are precipitation and ion exchange. Precipitation is a chemical process in which the chemical equilibrium of the waste stream is altered to reduce the solubility of the HMs, allowing the HMs to precipitate out as a solid phase that can be removed and separately managed. Ion exchange is a process that removes HMs from contaminated groundwater using synthetic resins as the immobile exchange medium. The exchange medium has a mobile ion that can be exchanged for a similarly charged ion in the contaminated water stream. The CORA cost model assumes that the HMs are recovered for recycling rather than disposal.

As noted in Section 4.1, based on the data examined for this report, HMs contamination occurs in conjunction with either EXPs and/or VOCs contamination. Therefore, remedial actions to remove HMs would be done in addition to the actions required for extraction and treatment for EXPs or VOCs contamination. The appropriate technology (precipitation or ion exchange) depends on both the HMs present and the cleanup objectives. Table 4.3 shows the unit HMs treatment costs for the treatment rates discussed in Section 4.1. As noted, only the treatment component is included since HMs treatment is incremental to other remedial actions.

TABLE 4.3. CORA Model-Derived Treatment Cost Estimates ($/1000 gal) for Groundwater Contaminated with Heavy Metals

Cost Component	100 gpm	400 gpm	3000 gpm
Extraction	-	-	-
Precipitation/Ion Exchange	$8.00 to $10.00	$3.00 to $5.00	$1.00 to $2.00
Disposal of Treated Water	-	-	-
Monitoring	-	-	-
TOTAL	$8.00 to $10.00	$3.00 to $5.00	$1.00 to $2.00

Figure 4.6 shows the range of CORA model unit cost estimates for both precipitation and ion exchange. The figure shows that HMs removal costs are sensitive to the amount treated since significant capital costs are involved for both precipitation and ion exchange. As the treatment rates increase, these fixed capital costs are averaged over higher throughputs, and overall unit costs. The figure also shows that slightly higher costs are incurred if chromium is present in the wastewater. The additional cost is incurred because an additional process step is required to change the valence state of chromium so that it can be removed. The ranges of unit costs for precipitation and ion exchange treatment of groundwater contaminated with HMs shown on Table 4.3 correspond to the approximate ranges shown on Figure 4.6 for 100 and 400 gpm. The cost range shown on Table 4.3 for 3000 gpm was extrapolated from the CORA unit cost estimate data on the figure since the CORA cost model does not consider treatment rates as high as 3000 gpm for HMs treatment.

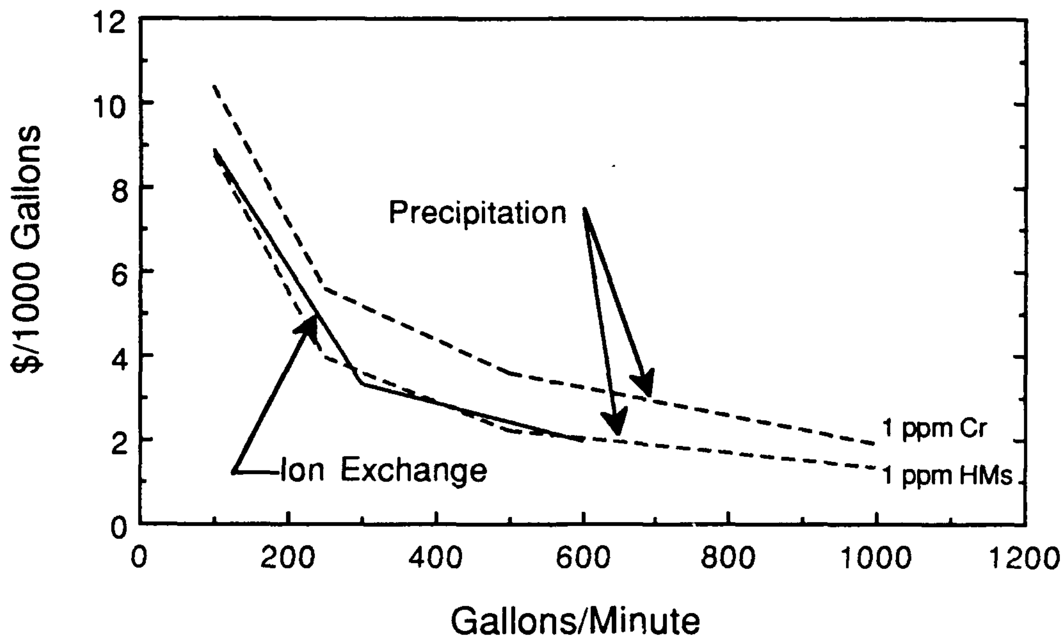

FIGURE 4.6. CORA Model-Derived Unit Cost Estimates for Treating Heavy Metals-Contaminated Groundwater

4.2.3 Unit Cost for Remedial Actions Involving Groundwater Contaminated with Volatile Organic Compounds

The reference remedial action technologies for treating groundwater contaminated with VOCs are air stripping, followed by vapor-phase carbon treatment to remove the organic compounds from the air stream. Air stripping is typically performed by pumping contaminated water downward through a tower of porous packing material while air is blown upward through the tower. The VOCs volatilize and are collected with the air stream at the top of the tower. This air stream is then vented if concentrations are below relevant regulatory limits, or it is passed through a vessel containing activated carbon to collect the organic compounds. The carbon is typically replaced or regenerated. This report assumes for cost estimating purposes that removal of the VOCs from the air stream will be required.

The major cost components for treatment of groundwater contaminated with VOCs are 1) extraction, 2) air stripping, 3) vapor-phase carbon treatment, 4) disposal of treated water, and 5) monitoring. The unit costs for each of these components for treatment rates of 100 and 3000 gpm (as discussed in Section 4.1) are shown on Table 4.4. The assumptions and the CORA model unit cost estimates for extraction, disposal of treated groundwater, and monitoring are the same as for treatment of groundwater contaminated with EXPs and are discussed in Section 4.2.1. The assumptions and CORA model unit cost estimates for air stripping and vapor-phase carbon treatment are discussed below.

Figure 4.7 shows the CORA model unit cost estimates for air stripping for the treatment rates and concentration variations discussed in Section 4.1. The figure shows that air stripping is generally less expensive than the previously discussed treatment technologies, is fairly insensitive to treatment rate, and is fairly insensitive to contamination level and contaminant volatility. The ranges of unit costs for air stripping of groundwater contaminated with VOCs shown on Table 4.4 correspond to the approximate ranges shown on Figure 4.7 for 100 and 3000 gpm.

Figure 4.8 shows the CORA model unit cost estimates for vapor-phase carbon treatment of the air stream from air stripping groundwater

TABLE 4.4. CORA Model-Derived Treatment Cost Estimates ($/1000 gal) for Groundwater Contaminated with Volatile Organic Compounds

Cost Component	100 gpm	3000 gpm
Extraction	$1.00 to $6.00	$1.00 to $6.00
Air Stripping	$1.00	$0.10 to $0.20
Vapor-Phase Carbon	$2.00 to $3.00	$0.15 to $0.50
Disposal of Treated Water	$0.50 to $2.50	$0.50 to $2.50
Monitoring	$1.50	$0.50
TOTAL	$6.00 to $14.00	$2.00 to $10.00

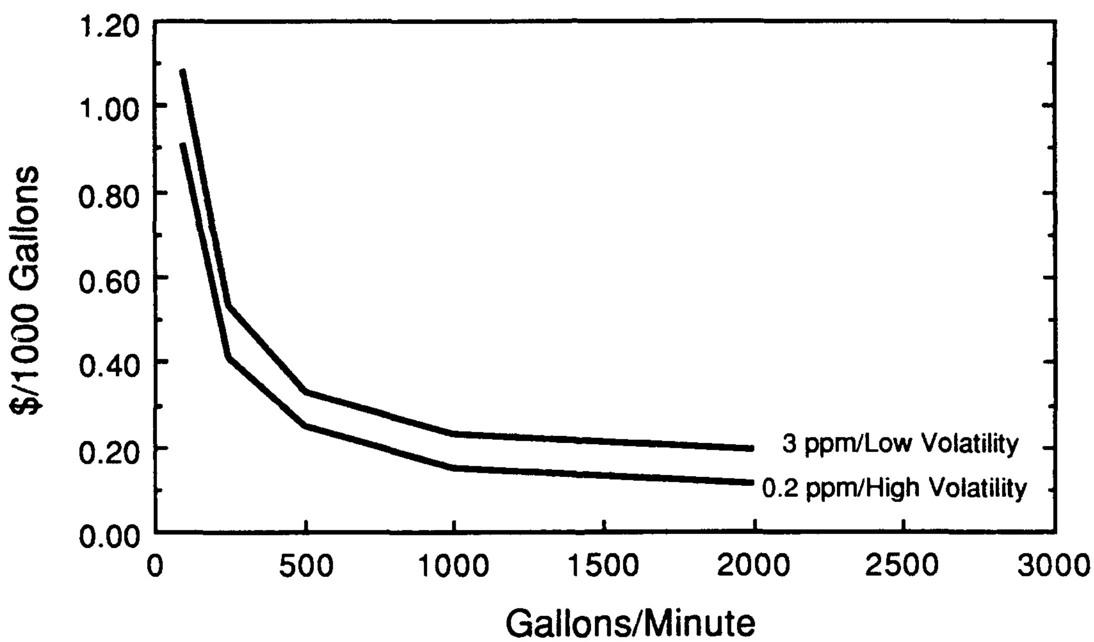

FIGURE 4.7. CORA Model-Derived Unit Cost Estimates for Air Stripping Volatile Organic Compounds-Contaminated Groundwater

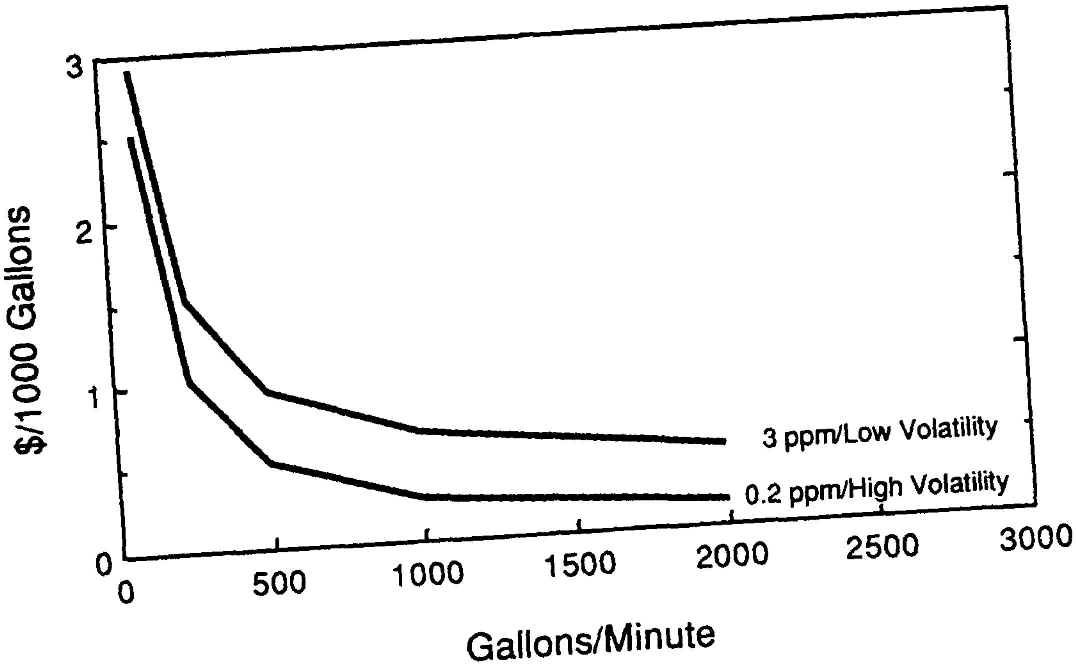

FIGURE 4.8. CORA Model-Derived Unit Cost Estimates for Vapor-Phase Carbon Treatment for Volatile Organic Compounds-Contaminated Groundwater

contaminated VOCs. The figure indicates that this unit cost component is insensitive to the treatment rate for rates over 400 to 500 gpm, but the cost component is sensitive to the range of concentrations considered. This variation with concentration is due to variation in the carbon cost with concentration. The ranges of unit costs for vapor-phase carbon treatment of contaminated groundwater shown on Table 4.4 correspond to the approximate ranges shown on Figure 4.8 for 100 and 3000 gpm.

4.3 UNIT COST TARGETS AND PAYOFFS FOR ALTERNATIVE TECHNOLOGIES FOR GROUNDWATER REMEDIAL ACTIONS

This section describes the unit cost targets for alternative groundwater remedial action technologies that are used in Section 5 as one of the bases for assessing categories of alternative groundwater remedial action technology. The corresponding payoff, in terms of DA IRP cost savings, is also discussed. These estimates for potential savings are used in Section 6 as a factor in determining priorities among alternative R&D investments.

Unit cost targets for developmental groundwater treatment technologies were chosen to be lower than the reference technology unit cost; lower unit cost targets result in a significant IRP cost savings relative to the reference cost for the remedial action activity. Again, some judgment was used to avoid establishing unit cost targets so low that they are unrealistic or unachievable based on current expectations for alternative technologies.

The same major types of uncertainties that make the potential savings for developmental soil treatment technologies difficult to estimate make potential savings for successfully developing alternative technologies difficult to estimate. There are large uncertainties in the amount of contaminated groundwater for those Army installations for which data were available. The unit cost for the reference technology is uncertain, depending on specific application conditions such as the amount of groundwater to be treated or processed and its degree of contamination. Finally, the amount that would be saved if the developmental technology were applied at other installations, to other wastes at the installations considered, or for longer time periods is unknown. Because of these uncertainties, broad ranges of potential savings are estimated in this section, and calculations performed to make these estimates make liberal use of rounding and approximating. The current basis for this estimate does not warrant calculational precision.

Sections 4.3.1, 4.3.2, and 4.3.3 describe the developmental technology unit cost targets and the corresponding IRP cost savings for groundwater contaminated with EXPs, HMs, and VOCs, respectively. Table 4.5 summarizes those unit cost targets and savings. Where target unit costs are shown in Table 4.5 as a range, the appropriate target unit cost depends on the amount of groundwater to be treated at each installation. The range of savings shown for each category corresponds to the estimated DA IRP cost reductions for the portion of the total amount of contaminated groundwater discussed in Section 4.2. Requirements for additional remedial actions for contamination from other sources or for longer treatment periods could increase the potential savings that would be realized if the developmental technologies achieve target unit costs.

TABLE 4.5. Unit Cost Targets and Estimated DA IRP Cost Savings for Developmental Groundwater Treatment Technologies

Treatment Technology	Target Cost	Estimated Savings
Onsite Treatment		
Explosives	$1.50/1000 gallons	$30 to $175 million
Heavy Metals	$1.00 to $7.00/1000 gallons	$10 to $140 million
Volatile Organic Compounds	$0.25 to $70/1000 gallons	$10 to $140 million
In Situ Treatment		
Explosives	$0.08/gallon	$25 to $450 million
Volatile Organic Compounds	$0.04/gallon	$15 to $770 million

4.3.1 Unit Cost Targets and Payoffs for Remedial Actions Involving Groundwater Contaminated with Explosives

The reference remedial action for groundwater contaminated with EXPs is extraction followed by GAC treatment and reinjection or surface discharge of the treated groundwater. Based on the installation data considered in Section 4.1, treatment of 100 to 400 gpm of contaminated groundwater will be required for 20 or more years at 16 installations. For these assumptions, approximately 20 to 70 billion gallons of contaminated groundwater would require treatment (100 gpm to 400 gpm for 20 years at 16 installations).

Two different types of cost targets were considered for developmental technologies for remedial actions involving groundwater contaminated with EXPs. For onsite technologies after extraction of the groundwater from the contaminated aquifer, the appropriate target is a technology that replaces GAC but has a lower unit cost. For technologies that can be applied in situ and which do not require extraction of the contaminated groundwater, the appropriate developmental target is a unit cost that is less than the total reference remedial action unit cost.

The unit cost estimates for GAC treatment range from $3.00 to $4.50 per 1000 gallons at a treatment rate of 100 gpm to $2.00 to $4.00 for a treatment rate of 400 gpm. A cost target of $1.50 per 1000 gallons was adopted for alternative onsite treatment technologies. If this target were achieved, a savings of $1.50 to $3.00 per 1000 gallons would be realized for treatment

rates of 100 gpm, and $0.50 to $2.50 per 1000 gallons would be saved at treatment rates of 400 gpm. If the target unit cost of $1.50 per 1000 gallons could be achieved, $30 to $175 million could be saved (20 billion gallons at $1.50 per 1000 gallons savings to 70 billion gallons at up to $2.50 per 1000 gallons savings).

A cost target for an in situ treatment technology for EXPs contamination must be expressed in slightly different terms. The cost of in situ treatment is generally proportional to the original volume of contaminated groundwater, rather than the volume of water that must be treated if it is extracted. Onsite treatment involves treating many times the volume that is originally contaminated, as uncontaminated water is flushed through the contaminated region, extracted, and treated. Typically, one to two times the original volume of contaminated water is treated per year, depending on hydrological considerations such as the hydraulic conductivity and recharge characteristics of the aquifer. In 20 years, 20 to 40 times the original contaminated volume is treated. In situ treatment typically requires treating the contaminated volume only once.

For this report, target unit costs for in situ groundwater treatment technologies were determined assuming that the treatment rates considered correspond to treating one volume of contaminated water per year. Using this assumption, a treatment rate of 100 gpm would correspond to an original contamination volume of approximately 50 million gallons per installation, and a treatment rate of 400 gpm would correspond to a contamination volume of approximately 200 million gallons per installation. A target unit cost of $0.08 per gallon of contaminated groundwater was adopted for in situ treatment of groundwater contaminated with EXPs. This value was selected because it would result in a slight savings even if groundwater extraction and discharge costs were at the lower end of their estimated range.

To estimate the potential savings if this target is achieved through R&D, it was assumed that in situ treatment could be performed at the 12 installations with only EXPs-contaminated groundwater. Installations with EXPs and either HMs or VOCs contamination would require more complex in situ treatment and were not considered. If the target unit costs for in situ

treatment were achieved, potential savings would range from $25 million to $450 million. The lower estimate is based on in situ treatment of approximately 50 million gallons of groundwater (which corresponds to 100 gpm) for $0.08 per gallon at 12 installations versus treatment of 100 gpm at 12 installations for 20 years at a cost of $6.00 per 1000 gallons (the lower limit of the estimated reference technology treatment cost range for 100 gpm). The higher estimate is based on in situ treatment of approximately 200 million gallons of groundwater (which corresponds to 400 gpm) for $0.08 per gallon at 12 installations versus treatment of 400 gpm at 12 installations for 20 years at a cost of $13.00 per 1000 gallons (the upper limit of the estimated reference technology treatment cost range for 400 gpm).

4.3.2 Unit Cost Targets and Payoffs for Remedial Actions Involving Groundwater Contaminated with Heavy Metals

The reference remedial action for groundwater contaminated with HMs is extraction followed by either ion exchange or precipitation treatment and reinjection or surface discharge of the treated groundwater. Based on the installation data considered in Section 4.1, treatment of 100 to 400 gpm of HMs contaminated groundwater will be required for 20 years or more at three installations, and 100 to 3000 gpm of contaminated groundwater will be required for 20 or more years at four installations. For these assumptions, approximately 10 to 70 billion gallons of contaminated groundwater would require treatment (100 gpm for 20 years at seven installations to 400 gpm for 20 years at three installations and 3000 gpm for 20 years at four installations).

A target cost was determined only for onsite treatment of groundwater contaminated with HMs. Based on the information examined in Section 4.2, treatment of HMs contamination will be required in conjunction with either or both EXPs and VOCs. The estimated unit cost for the reference technology varies substantially with the amount of water treated ($8.00 to $10.00 per 1000 gallons for 100 gpm, $3.00 to $5.00 per 1000 gallons for 400 gpm, and $1.00 to $2.00 per 1000 gallons for 3000 gpm). A target unit cost range with a similar variation was selected for developmental technologies for onsite

treatment of groundwater contaminated with HMs (unit costs of $7.00, $3.00, and $1.00 per 1000 gallons for treatment rates of 100 gpm, 400 gpm, and 3000 gpm, respectively). This range was chosen such that a small savings would be realized even if the reference technology costs were at the lower end of their estimated range.

The estimated savings in IRP cost if the target unit costs are achieved as the result of R&D are approximately $10 million to $140 million. The lower end of this range assumes savings of $1.00 per 1000 gallons at seven installations with treatment rates of 100 gpm for 20 years. The upper end of the range assumes a savings of $1.00 per 1000 gallons at three installations with treatment rates of 400 gpm for 20 years and four installations with treatment rates of 3000 gpm for 20 years.

4.3.3 Unit Cost Targets and Payoffs for Technologies for Remedial Actions Involving Groundwater Contaminated with VOCs

The reference remedial action for groundwater contaminated with VOCs is extraction, air stripping, vapor-phase carbon treatment of the air stream to recover organic compounds, and reinjection or surface discharge of the treated groundwater. Based on the installation data considered in Section 4.1, treatment of 100 to 3000 gpm of VOCs-contaminated groundwater will be required for 20 or more years at nine installations. For these assumptions, approximately 10 to 280 billion gallons of contaminated groundwater would require treatment (100 to 3000 gpm for 20 years at nine installations).

The reference technology unit costs for onsite treatment of groundwater contaminated with VOCs are relatively low compared with those for the other contamination categories. The total unit cost for air stripping and vapor-phase carbon treatment varies from $3.00 to $4.00 per 1000 gallons for treatment rates of 100 gpm to $0.25 to $0.70 for treatment rates of 3000 gpm. Target unit costs at or below the lower end of these ranges were selected ($2.00 per 1000 gallons for treatment rates of 100 gpm, $0.20 per 1000 gallons for treatment rates of 3000 gpm).

If this target unit cost can be achieved by developing an alternative onsite treatment technology for groundwater contaminated with VOCs, IRP cost savings of approximately $10 million ($1.00 per 1000 gallons at nine installations with treatment rates of 100 gpm for 20 years) to $140 million ($0.50 per 1000 gallons at nine installations with treatment rates of 3000 gpm for 20 years) could be achieved.

As noted in Section 4.3.1, target unit costs for in situ groundwater treatment technologies were determined by assuming that the treatment rates considered correspond to treating one volume of contaminated water per year. Using this assumption, a treatment rate of 100 gpm would correspond to an original contamination volume of approximately 50 million gallons, and a treatment rate of 3000 gpm would correspond to a contamination volume of approximately 1.6 billion gallons. A target unit cost of $0.04 per gallon of contaminated groundwater was adopted for in situ treatment of groundwater contaminated with EXPs because it would result in a slight savings even if groundwater extraction and discharge costs were at the lower end of their estimated range.

To estimate the potential savings if this target is achieved through R&D, it was assumed that in situ treatment could be performed at the three installations with only groundwater contaminated with VOCs. Installations with VOCs plus either or both EXPs and HMs contamination would require different in situ treatment and were not considered. If the target unit cost for in situ treatment were achieved, potential savings range from $15 million to $770 million. The lower estimate is based on in situ treatment of approximately 50 million gallons of groundwater (which correspond to 100 gpm) for $0.04 per gallon at three installations versus treatment of 100 gpm at three installations for 20 years at a cost of $6.00 per 1000 gallons (the lower limit of the estimated reference technology treatment cost range for 100 gpm). The higher estimate is based on in situ treatment of approximately 200 million gallons of groundwater (which correspond to 400 gpm) for $0.04 per gallon at three installation versus treatment of 3000 gpm at three installations for 20 years at a cost of $10.00 per 1000 gallons (the upper limit of the estimated reference technology treatment cost range for 3000 gpm).

5.0 TECHNOLOGY CATEGORY RANKING

The previous two sections discussed 1) the Army's remedial action requirements (amount of contaminated soil or groundwater to be treated), 2) the costs associated with cleaning up the contamination using the currently identified technologies, and 3) the unit cost targets and corresponding IRP payoff identified from the above information. The unit cost targets and potential payoff are used in Section 6 with a ranking of the technology categories (on the basis of the likelihood that the technology could meet the unit costs) to prioritize potential USATHAMA R&D investments. This section describes the approach used to rank the technology categories (physical, chemical, thermal, and biological) and presents the results from the ranking exercise.

The basis for ranking the technology categories was the likelihood that they could successfully meet the target unit cost for a particular remedial action category. The approach for ranking the technology categories is to 1) generate a list of potentially feasible treatment technologies for each remedial action category (e.g., EXPs-contaminated soil, HMs-contaminated soil, etc.), 2) identify the unit cost of each technology, 3) rank the technology categories based on unit cost and stage of development, and 4) assign a probability estimate to the qualitative rankings.

First, lists of potentially feasible treatment technologies for each waste category were generated using USATHAMA technology evaluation studies (Bove et al. 1983 and 1984). These lists were supplemented with representative technologies that were developed after the studies were performed. The lists of treatment technologies (Tables B.1 through B.6 in Appendix B) are not comprehensive; that was beyond the scope of this study. Instead, the lists of technologies represent the type of technologies that are identified in the literature.

Next, unit costs were identified for each technology based on information from the open literature and from vendors. This information was used to evaluate each waste category based on the following criteria:

- the number of technologies that could potentially meet unit cost requirements (the target unit costs developed in Sections 3 and 4 are summarized in Table 5.1) - The larger the number of "potential" technologies, the higher the rating.

- the stage of development of each technology - A lower percentage of technologies in the bench-scale (as opposed to pilot-scale) stage of development reach the demonstration phase primarily due to the uncertainty in scale-up relationships.

The evaluation of the technology categories relative to these criteria resulted in three distinct rankings (high, medium, and low) that appear to have different potentials for yielding a technology that can meet the relevant unit cost target.

Finally, ranges of quantitative values were assigned to the qualitative rankings. These values, expressed in percentages, represent the likelihood (or probability) that a category with that qualitative ranking would produce a technology that can meet the target unit cost for a particular application. Assigning numbers to represent "likelihood of success" for a specific cost is the same as identifying a single point on a cumulative probability distribution curve. Cumulative probability curves are commonly used in evaluating R&D activities because "no single number is adequate to describe what is

TABLE 5.1. Technology Unit Cost Targets

Remedial Action	Unit Cost Target
Soil	
Explosives	$100/ton, $50/ton
Heavy Metals	$200/ton, $300/ton
Volatile Organic Compounds	$50/ton
Groundwater	
Explosives (onsite)	$1.50/1000 gallons
Explosives (in situ)	$0.08/gallon
Heavy Metals (onsite)	$1.00 to $7.00/1000 gallons
Volatile Organic Compounds (onsite)	$0.20 to $0.70/1000 gallons
Volatile Organic Compounds (in situ)	$0.04/gallon

known about likely performance [of R&D processes] and ... no objective probability can be assigned to the uncertainty" (Boyd and Regulinski 1979). These cumulative probability curves represent the judgment of experts. An example of a probability distribution curve is presented in Figure 5.1 (EPRI 1979). This figure indicates that there is a 10% chance that the capital cost will be less than \$470/kWh-yr and a 90% chance that it will be less than \$825/kWh-yr.

For this study, a more appropriate example might be that one can be 100% sure that a treatment technology in the thermal category (e.g., incineration) can be developed to treat EXPs-contaminated soils for \$1000/ton. However, it is less certain that this category can produce a technology capable of treating contaminated soil for \$400/ton and almost certain that even with additional R&D a thermal treatment technology cannot be developed to treat waste for \$100/ton.

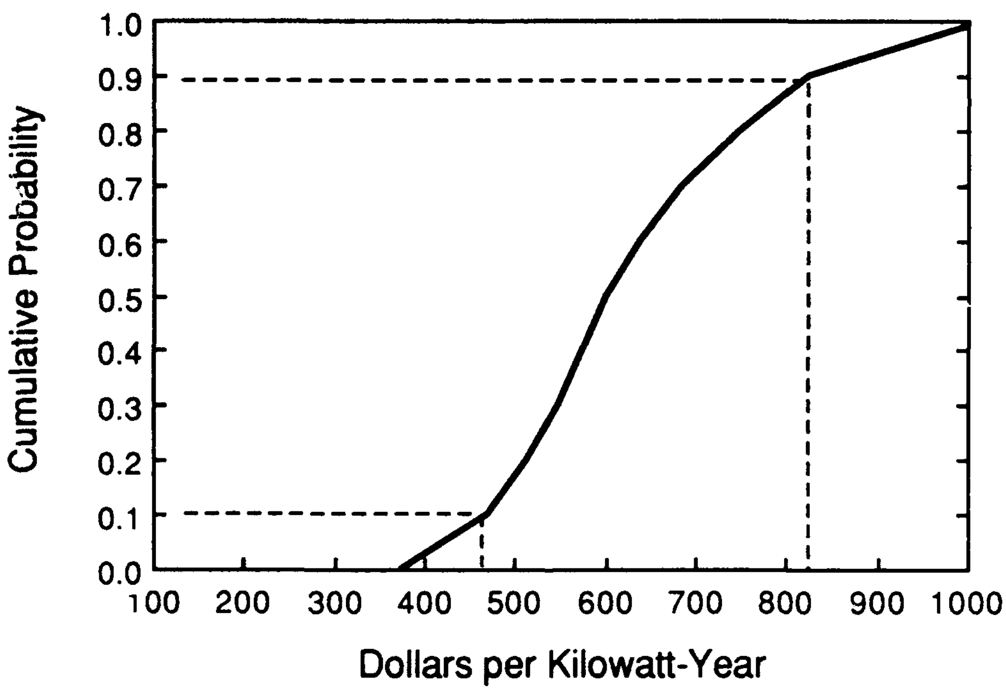

FIGURE 5.1. Cumulative Probability Distribution on the Capital Cost of a Gasification-Combined Cycle Plant (EPRI 1979)

The estimate of the likelihood that a particular technology (or technology category) will meet the target unit cost is best determined by the judgment of experienced researchers. These judgments are somewhat subjective; therefore, a range of percentages was used when assigning values to the rankings. The exact value assigned to each ranking is much less important for this study than the relative values between the rankings. A description of the rankings is given in Table 5.2. The likelihood of success, in percent, assigned to each ranking is as follows:

1. A probability range of 50% to 70% was assigned to the "high (H)" ranking. The categories with a high ranking included technologies that are mostly in the demonstration stage of development with estimated unit costs at or below the target unit cost. The scale-up relationships for these technologies have been proven, but their application to a variety of sites and waste characteristics must still be demonstrated. The technologies in this stage of development have a better than one in two chance of success, and they probably have a three in four chance of success.

2. A probability range of 20% to 30% was assigned to the "medium (M)" ranking. The categories with a medium ranking included technologies that are mostly in the pilot-scale stage of development, with estimated unit costs at or below the target unit cost. The technical basis on which these technologies are based has been shown to be sound, and they have been developed through the first step of the scale-up process. One out of three technologies in this stage of development is likely to reach full-scale.

3. A probability range of 10% to 15% was assigned to the "low (L)" ranking. This category consists of two types of technologies: technologies that were mostly in the bench-scale stage of development (designated by "L_t"), and technologies that were mostly fully developed, yet had unit costs slightly above the target unit cost (designated by "L_c"). Reliable cost information for technologies in the bench-scale stage is typically not available. The technologies in this stage of development have been shown to be successful under ideal conditions, although the scale-up relationships have not yet been proven. One out of eight to ten technologies in this stage of development are likely to reach full-scale. The fully developed, high-cost technologies are slightly less promising for investing R&D funds than the technologies that have not yet been developed but are expected to have low unit costs.

The ranking and "likelihood of success" for each technology category in each contamination category are summarized in Table 5.3. A list of the

TABLE 5.2. Description of the Rankings

Ranking	Likelihood of Success	Description
High (H)	50% to 70%	A category with the "high" ranking consists of technologies that are primarily in the demonstration stage of development with estimated unit costs at or below the target unit cost. These technologies have not yet successfully demonstrated their applicability to a broad range of site and waste characteristics.
Medium (M)	20% to 30%	A category with the "medium" ranking consists of technologies that are primarily in the pilot-scale stage of development, with estimated unit costs at or below the target unit cost. These technologies have not yet shown that they can be successfully scaled to full-scale.
Low (L_t)	15%	A category with the "low" ranking consists of technologies that are primarily in the bench-scale stage of development. These technologies have shown that, under ideal conditions, they are successful.
Low (L_c)	10%	A category with the "low - because of cost" ranking consists mostly of fully developed treatment technologies with unit costs slightly above the target unit cost.

"potential" technologies used to develop Table 5.3 and other worksheets are in Appendix B. The results shown on Table 5.3 for each contamination category are discussed in the following sections.

5.1 TECHNOLOGY CATEGORY RANKING FOR SOIL CONTAMINATED WITH EXPLOSIVES

Table 5.3 indicates that two of the treatment technology categories (chemical and biological) appear to have the potential for yielding a technology that could meet the target unit cost of $100/ton. These technology categories were each assigned a "medium" ranking based on the criteria described in this section. The biological category was assigned a medium ranking because most of the technologies identified in this category are in

TABLE 5.3. Probability of Meeting Target Unit Costs

Remedial Action Category	Target Unit Cost	Technology Category: Physical	Chemical	Thermal	Biological
Soil					
Explosives	\$100/ton		M[a] (20% to 30%)	-	M (20% to 30%)
	\$50/ton		L_c[b] (10%)		
Heavy Metals	\$200/ton	M (20% to 30%)	L_t[c] (15%)	L_c (10%)	
	\$300/ton	M (20% to 30%)	L_t (15%)	H[d] (50% to 70%)	
Volatile Organic Compounds	\$50/ton		L_c (10%)	M (20% to 30%)	M (20% to 30%)
Groundwater					
Explosives					
Onsite	\$1.50/Kgal	M (20% to 30%)	L_c (10%)		L_c (10%)
In Situ	\$0.08/gal				L_t (15%)
Heavy Metals	\$1.00 to \$7.00/Kgal		L_t (15%)		L_c (10%)
Volatile Organic Compounds					
Onsite	\$0.20 to \$0.70/Kgal		L_c (10%)		L_c (10%)
In Situ	\$0.04/gal				L_t (15%)

(a) M - medium likelihood of success; these technologies are primarily pilot-scale with costs at or below the target unit cost.
(b) L_c - low likelihood of success because of cost; these technologies are primarily fully-developed with costs slightly above the target unit cost.
(c) L_t - low likelihood of success; these technologies are primarily bench-scale.
(d) H - high likelihood of success; these technologies are primarily in the demonstration stage of development with costs at or below the target unit cost.

the pilot-scale stage of development (see Table B.7). The chemical category was assigned a medium likelihood of producing a technology that could meet the $100/ton target unit cost and a low ranking with respect to meeting the target unit cost of $50/ton, because most of the technologies identified in this category have estimated unit costs slightly above these target unit costs.

5.2 TECHNOLOGY CATEGORY RANKING FOR SOIL CONTAMINATED WITH HEAVY METALS

The physical treatment technology category is identified as having the highest likelihood of success of producing a technology that could meet a target unit cost of $200/ton for treating soil contaminated with HMs. This category was assigned a medium ranking because most of the technologies identified are in the pilot-scale stage of development (see Table B.7). The thermal treatment technology category becomes the most promising category when the target unit cost is increased to $300/ton, primarily because it contains several promising technologies that are typically in the demonstration stage of development.

5.3 TECHNOLOGY CATEGORY RANKING FOR SOIL CONTAMINATED WITH VOLATILE ORGANIC COMPOUNDS

Both the biological and thermal categories were ranked medium because the potential technologies identified (see Table B.7) are typically in the pilot-scale stage of development. The chemical treatment technology category was ranked low because it typically contained technologies that are fully developed yet have treatment costs slightly above the target unit cost.

5.4 TECHNOLOGY CATEGORY RANKING FOR GROUNDWATER CONTAMINATED WITH EXPLOSIVES

The physical category for cleanup of groundwater contaminated with EXPs has the highest likelihood of success of producing a technology with a unit cost less than that estimated for the currently identified treatment technology (GAC). This category was ranked medium because the technologies identified in Table B.7 as "potential technologies" are primarily in the

pilot-scale stage of development. The onsite chemical and biological treatment categories have technologies that could treat groundwater contaminated with EXPs, but their estimated unit costs are greater than the target unit costs, and therefore assigned a low ranking. The in situ biological treatment technology category was assigned a low ranking because most of the technologies in this category that were identified as "potential technologies" (see Table B.7) are in the bench-scale stage of development.

5.5 TECHNOLOGY CATEGORY RANKING FOR GROUNDWATER CONTAMINATED WITH HEAVY METALS

Two technology categories were identified that have the potential to produce a technology that could meet the target unit cost. Both categories (physical and biological) were ranked low. The physical treatment technology category was ranked low because most of the technologies in that category that were identified as "potential technologies" (see Table B.7) are in the bench-scale stage of development. The biological treatment technology category was ranked low for similar reasons.

5.6 TECHNOLOGY CATEGORY RANKING FOR GROUNDWATER CONTAMINATED WITH VOLATILE ORGANIC COMPOUNDS

The onsite chemical and biological treatment technology categories identified for this remedial action category have low rankings primarily because the reference technology (air stripping followed by vapor phase carbon) is inexpensive to operate, and therefore the target unit cost is difficult to attain. The in situ biological treatment technology category was assigned a low ranking primarily because technologies in this category are primarily in the bench-scale stage of development.

6.0 R&D INVESTMENT STRATEGIES

This section describes the evaluation of potential R&D strategies for developing new or innovative alternative technologies for DA IRP remedial action activities. For each of four R&D funding levels (current funding, 150%, 200%, and 300% of current funding), the preferred mix of R&D investments (soil or groundwater contamination category, technology category) are identified, and the corresponding potential reductions in the DA IRP cost are estimated.

Section 6.1 summarizes some of the key assumptions made in formulating R&D strategies for varying levels of R&D funding, and Section 6.2 describes the evaluation methodology. In Section 6.3 the preferred and the backup technology categories to be developed for each contamination category are identified. Section 6.4 includes the rationale for the four R&D strategies that are developed and the estimated DA IRP cost savings for each.

6.1 USATHAMA R&D FUNDING LEVEL ASSUMPTIONS

The objective of this report is to develop R&D funding strategies for alternative R&D funding levels. To do so with absolute rigor would require detailed knowledge of the projected USATHAMA R&D budget for this type of technology development and detailed estimates for the cost of identifying and developing specific technologies from each of the alternative technology categories. That level of detail is beyond the scope of this report. Rather, representative assumptions are made about future USATHAMA R&D funding levels and the average cost for developing specific technologies.

Current USATHAMA R&D efforts conducted in support of the DA IRP include the evaluation of commercially available state-of-the-art technology for installation restoration and development of new, innovative technology that is more economical and efficient than existing technology. The purpose of USATHAMA's IR Decontamination Technology Development Program (Project AF25) is to provide R&D support for required assessment and cleanup activities at Army installations. Project AF25 funding is currently being supplemented with Defense Environmental Restoration Account (DERA) funding.

The approximate annual R&D funding available for these activities is $3 million per year, or approximately $15 million for FY 1991 through FY 1995. Previous USATHAMA experience indicates that approximately $3 to $4 million (over three to five years) is a typical cost for developing a technology to the point of readiness for field application.

Based on these approximate budget and cost estimates, it is assumed that current funding for FY 1991 through FY 1995 will allow development of approximately four new technologies. Increased funding to levels of 150%, 200% and 300% of current funding would allow development of six, eight, and twelve new technologies, respectively. These estimates for the number of technology categories that could be considered are obviously approximate. Actual funding required for a specific mix of technology development activities would require a much more rigorous estimating process, which is beyond the scope of this report.

6.2 METHODOLOGY FOR EVALUATING ALTERNATIVE R&D STRATEGIES

The primary objectives for USATHAMA R&D in support of the DA IRP are to ensure that available technology will allow DA IRP activities to comply with relevant regulations and to develop technology that will allow these activities to be cost-effective. It is assumed for this report that the reference technologies for performing the various DA IRP activities satisfy regulatory concerns. Therefore, cost is used as the primary consideration for whether USATHAMA should develop an alternative technology.

The evaluations described in the following sections use the ranges of estimated potential DA IRP cost reductions developed in Sections 3 and 4, along with the evaluation of alternative technology categories described in Section 5, to assess both the potential payoff and probability-weighted payoff for pursuing development within a technology category. The ranges of potential payoffs estimated for meeting development targets in the various technology categories were broad, based on large uncertainties in both the remedial action requirements (amount of treatment required) and the reference technology unit cost. In addition, the evaluation of alternative technology categories was subjective, and the results were expressed as broad ranges of

probability (or likelihood) for successfully identifying and developing an alternative technology from a technology category. Because these inputs to the evaluation are uncertain, no attempt is made to discriminate between alternative R&D investments based on small differences in potential or probability-weighted DA IRP savings. Distinctions are made between payoffs for alternative technology categories only if the difference in estimated payoff is large in proportion to the magnitude of the estimated payoffs.

Several steps are performed in the evaluation process. These steps are listed below:

1. Identify the preferred and a backup technology category for each contamination category.

2. Estimate the incremental potential payoff (DA IRP cost savings) and incremental probability-weighted payoff for the preferred and backup technology categories for each contamination category.

3. Rank the potential R&D investments (preferred and backup technology categories for all contamination categories) based on incremental probability-weighted payoff and incremental potential payoff.

4. Group the ranked technology categories into R&D investment strategies for each of the assumed levels of R&D funding, and estimate the DA IRP cost savings for each R&D investment strategy.

Steps 1 and 2 for this process are discussed in Section 6.3. Section 6.4 describes steps 4 and 5 and gives the overall results for the evaluation.

6.3 TECHNOLOGY CATEGORIES AND PAYOFFS FOR EACH CONTAMINATION CATEGORY

The preferred order of selection of technology categories within a contamination category is generally based on the categories' rankings discussed in Section 5; the highest ranking technology category is selected as the preferred category, and the second highest is identified as the backup technology category. If two technology categories have the same rank (both "medium" for example), then the preferred is identified based on various secondary characteristics or considerations.

Two different types of payoff are estimated for each technology category. The incremental potential payoff is the estimated decrease in DA IRP

costs that could be achieved by successfully developing a technology within the category. Probability-weighted incremental payoff is a measure of the weighted average return for an investment and is often referred to in decision analysis or investment analysis literature as the "expected value." It is a measure of how much profit (or savings), on the average, each investment of the type under consideration would yield (Holloway 1979).

For the preferred technology category for a contamination category, the incremental potential payoff is the estimated payoff for the contamination category, as estimated in Sections 3 and 4. The incremental potential payoff for the backup technology category is the amount that savings could increase beyond that estimated for the preferred technology with increased funding levels. In most cases the incremental potential payoff for a backup technology category is zero.

The incremental probability-weighted payoff for both the preferred and backup technology category is estimated. For the preferred technology category, the incremental probability-weighted payoff is the estimated potential payoff for the contamination category from Sections 3 or 4 multiplied by the subjective estimate from Section 5 of the probability of successfully developing a technology from the technology category.

The incremental probability-weighted payoff for the backup technology category is slightly more complicated to estimate. It is the increase in the probability-weighted savings if both technology categories are pursued rather than just the preferred technology category. Calculating this incremental probability-weighted payoff requires computing the probability or likelihood for each of the four possible combinations of successful or unsuccessful development of the preferred and backup technology categories and the associated payoff for each of the combinations. The probability of each combination is multiplied by its payoff, and these products are summed to determine the probability-weighted payoff for pursuing development of both categories. The incremental probability-weighted payoff for the backup category is the difference between the probability-weighted payoff for developing both and the probability-weighted payoff for developing the preferred category.

It is a measure of how much the average or expected DA IRP cost reduction would be increased by investing in a second technology category for a contamination category.

Table 6.1 summarizes the data from Sections 3, 4, and 5 that are required for these evaluations. In Table 6.2, the preferred and backup technology categories for each contamination category are identified, as well as the estimated incremental payoff and probability-weighted payoff. The results shown on Table 6.2 for each contamination category are discussed in the following sections.

6.3.1 Developmental Technologies for Soil Contaminated with Explosives

Table 6.1 shows that both the chemical and biological technology categories have a "medium" ranking, corresponding to a 20% to 30% likelihood that a technology within each could be developed to meet the target unit cost and realize the potential payoff estimated. In addition, the chemical technology category has a "low" (10% to 15%) likelihood of achieving a lower unit cost and a higher payoff. The biological technology category was selected as the preferred category, primarily because USATHAMA has already begun development of a composting process for treating soil contaminated with EXPs (Williams et al. 1988). The chemical technology category is therefore considered as the backup category for the contaminated soil.

The incremental potential payoffs and probability-weighted payoffs are calculated as described above. The incremental potential payoff for the biological technology category is the $100 to $300 million estimated for achieving the target unit cost. The incremental payoff for the chemical technology category is the additional $50 million that could be saved if a chemical technology could be successfully developed to meet the lower unit cost target.

The incremental probability-weighted payoff range for the biological technology category was estimated by taking the lower limit payoff ($100 million) times the lower limit probability estimate (20%) and the upper limit payoff ($300 million) times the upper limit probability estimate (30%), which results in the range of probability-weighted payoffs of $20 to $30 million shown on Table 6.2.

TABLE 6.1. Summary of Developmental Technology Unit Costs, DA IRP Savings, and Technology Category Rankings

Remedial Action Category	Target Unit Cost	Estimated DA IRP Cost Savings (10^6)(b)	Technology Category Rankings(a) Physical	Chemical	Thermal	Biological
Soil						
Explosives	$100/ton	$100 to $300	-	MEDIUM	-	MEDIUM
	$50/ton	$150 to $350	-	LOW	-	-
Heavy Metals	$200/ton	$20 to $35	MEDIUM	LOW	LOW	-
	$300/ton	less than $10	MEDIUM	LOW	HIGH	-
Volatile Organic Compounds	$50/ton	$20 to $30	-	LOW	MEDIUM	MEDIUM
Groundwater (Onsite)						
Explosives						
Onsite	$1.50/Kgal	$30 to $175	MEDIUM	LOW	-	LOW
In Situ	$0.08/gal	$25 to $450	-	-	-	LOW
Heavy Metals	$1.00 to $7.00/Kgal	$10 to $140	LOW	-	-	LOW
Volatile Organic Compounds						
Onsite	$0.20 to $0.70/Kgal	$10 to $140	-	LOW	-	LOW
In Situ	$0.04/gal	$15 to $770	-	-	-	LOW

(a) "HIGH" ranking means that there is an estimated 50% to 70% likelihood of successfully identifying and developing a technology from that category to meet the unit cost target. "MEDIUM" and "LOW" rankings are estimated to have 30% to 40% likelihood and 10% to 15% likelihood respectively of similar success. No entry means no technologies were identified that would meet the unit cost target.

(b) Estimated savings for the portion of overall DA IRP remedial action requirements discussed in Sections 3.2 and Section 4.2. Additional remedial action requirements for contamination from other sources or at other installations could increase estimated savings.

TABLE 6.2. Preferred and Backup Technology Categories

Preferred and Backup Technology Categories	Potential Payoff ($millions)	Probability-Weighted Payoff ($millions)
EXPs-Contaminated Soil		
Biological	$100 to $300	$20 to $90
Chemical	$50	$16 to $63
HMs-Contaminated Soil		
Physical	$20 to $35	$4 to $11
Thermal	$0	$4 to $5
VOCs-Contaminated Soil		
Biological	$20 to $30	$4 to $9
Thermal	$0	$3 to $6
EXPs-Contaminated Groundwater		
In Situ Biological	$25 to $450	$3 to $68
Onsite Physical	$0	$5 to $44
HMs-Contaminated Groundwater		
Onsite Chemical	$10 to $140	$1 to $21
Onsite Biological	$0	$1 to $18
VOCs-Contaminated Groundwater		
In situ Biological	$15 to $770	$2 to $117
Onsite Biological	$0	$1 to $17

The incremental probability-weighted payoff for additional investments in the development of a chemical technology is slightly more complex. The upper and lower limits for the probability-weighted payoff for the combined development of both processes is illustrated below for lower limit:

Biological Technology Development	Chemical Technology Development	Probability	Probability-Weighted Payoff
Unsuccessful	unsuccessful	(0.8) X (0.8)	(0.64) X $0
Successful	unsuccessful	(0.2) X (0.8)	(0.16) X $100
Unsuccessful	successful	(0.8) X (0.2)	(0.16) X $100
Successful	successful	(0.2) x (0.2)	(0.04) X $100
		TOTAL	$36 million

The composite probability-weighted payoff is $36 million, which, when compared with the lower limit probability-weighted payoff for developing only the biological category ($20 million), means that developing a chemical technology as a backup will add $16 million to the probability-weighted payoff. The upper limit incremental probability-weighted payoff of $63 million for developing a chemical technology is estimated in a similar way.

6.3.2 Developmental Technologies for Soil Contaminated with Heavy Metals

Table 6.1 shows that the physical technology category is the highest ranking category for the HMs soil contamination category. Both the chemical and thermal categories have "low" rankings, but the thermal category has a "high" ranking for achieving a slightly higher unit cost target; therefore, it was selected as the backup technology category. (The secondary target was considered in Section 3.3 because of the potential desirability of implementing an alternative to offsite disposal even if doing so does not reduce the current estimate for DA IRP cost.)

The incremental potential payoff and probability-weighted payoff for the preferred technology category and backup technology category were estimated as discussed in Section 6.3.1. These results are shown on Table 6.2.

6.3.3 Technology Categories for Soil Contaminated with VOCs

Both the biological and thermal technology categories for treatment of soil contaminated with VOCs have "medium" rankings. The biological technology category was selected as the preferred category based on its potential complement the preferred treatment technology category for groundwater contaminated with VOCs (see Section 6.3.6). Accordingly, the thermal technology was selected as the backup technology category.

The incremental potential payoff and probability-weighted payoff for the preferred technology category and backup technology category were estimated as discussed in Section 6.3.1. These results are shown on Table 6.2.

6.3.4 Treatment Technology for Groundwater Contaminated with Explosives

The selection of the preferred treatment technology category for groundwater contaminated with EXPs is an exception to the general rule of selecting

the technology category with the highest ranking. In situ biological technology with a "low" ranking was selected instead of the onsite physical technology category, which has a "medium" ranking. Even though the likelihood of successfully developing an onsite physical technology that meets the target is judged to be twice as great as that for developing an in situ biological technology that meets its target, the payoff for successfully developing an in situ biological process is estimated to be four times as large. The increased payoff for the in situ biological technology category makes it a better investment. The onsite physical technology category is therefore considered to be the backup technology category.

The incremental potential payoff and probability-weighted payoff for the preferred technology category and backup technology category were estimated as discussed in Section 6.3.1. These results are shown on Table 6.2.

6.3.5 Treatment Technology Categories for Groundwater Contaminated with Heavy Metals

Table 6.1 shows that both the physical and biological technology categories have "low" rankings. However, as discussed in Section 5, the physical technology category is slightly more promising and was therefore selected as the preferred technology. Accordingly, the biological technology category is considered to be the backup development for HMs-contaminated soil treatment.

The incremental potential payoff and probability-weighted payoff for the preferred technology category and backup technology category were estimated as discussed in Section 6.3.1. These results are shown on Table 6.2.

6.3.6 Treatment Technology Categories for Groundwater Contaminated with VOCs

All three of the potential technology categories shown on Table 6.2 for VOCs-contaminated groundwater treatment have "low" rankings. However, the in situ biological technology category has a higher potential payoff than the other two and was therefore selected as the preferred technology. The onsite biological technology category was selected as the backup technology category because it complements the preferred technology category.

The incremental potential payoff and probability-weighted payoff for the preferred technology category and backup technology category were estimated as discussed in Section 6.3.1. These results are shown on Table 6.2.

6.4 R&D STRATEGIES

R&D strategies (technology categories selected for development) corresponding to four different USATHAMA R&D funding levels were formulated from the data on Table 6.2. The evaluation process for determining the priority order for developing alternative technologies is discussed in Section 6.4.1. The alternative R&D strategies and their potential DA IRP cost savings are discussed in Section 6.4.2.

6.4.1 Priorities for Technology Development Categories

The next step in developing alternative R&D investment strategies is the ranking, or prioritization, of the technology categories based on the data on Table 6.2. The technology categories were sorted into an order of priority based on both their potential payoff and probability-weighted payoff; probability-weighted payoff was used as the first sorting criterion.

Probability-weighted payoff was selected as the first consideration because it more nearly reflects the likely return on an R&D investment; it takes into account both the potential reduction in DA IRP cost and the likelihood of realizing that reduction. In simple terms, the probability-weighted payoff reflects the average payoff that would be expected if a number of similar investments (with the same potential payoff and likelihood, or probability, of success) were made. There is no guarantee that any particular R&D investment will succeed, but selecting alternatives in the order of probability-weighted payoff enhances the likely payoff for an R&D strategy.

Potential payoff was used as the second-order sorting criterion. If the probability-weighted payoffs for two technology categories were similar, but one had a significantly higher potential payoff, it was selected as the higher priority.

Table 6.3 shows the results for prioritizing the technology categories as discussed above. As previously noted, because of the broad ranges of remedial action requirements and unit costs, and the subjective judgments implicit in the numerical results shown on Table 6.2, small differences were assumed not to be significant for the purposes of distinguishing between

TABLE 6.3. Priority for Technology Development Categories

Remedial Action/Technology Category		Probability-Weighted Payoff (10^6)	Potential Payoff (10^6)
1/2	VOCs-Contaminated Groundwater In Situ Biological	\$2 to \$117	\$15 to \$770
1/2	EXPs-Contaminated Soil Biological	\$20 to \$90	\$100 to \$300
3/4	EXPs-Contaminated Groundwater In Situ Biological	\$3 to \$68	\$25 to \$450
3/4	EXPs-Contaminated Soil Chemical	\$16 to \$63	\$50
5	EXPs-Contaminated Groundwater Onsite Physical	\$5 to \$44	\$0
6	HMs-Contaminated Groundwater Onsite Chemical	\$1 to \$21	\$10 to \$140
7/8	HMs-Contaminated Soil Physical	\$4 to \$11	\$20 to \$35
7/8	VOCs-Contaminated Soil Biological	\$4 to \$9	\$20 to \$30
9-12	HMs-Contaminated Groundwater Onsite Biological	\$1 to \$18	\$0
9-12	VOCs-Contaminated Groundwater Onsite Biological	\$1 to \$17	\$0
9-12	VOCs-Contaminated Soil Thermal	\$3 to \$6	\$0
9-12	HMs-Contaminated Soil Thermal	\$4 to \$5	\$0

alternative technology categories. Accordingly, many of the technology categories shown on Table 6.3 are considered equivalent based on these evaluations.

As noted on the Table 6.3, the first two technology categories (in situ biological treatment for VOCs-contaminated groundwater and biological treatment for EXPs-contaminated soil) are essentially equivalent. They have the largest probability-weighted payoffs of any of the technology categories.

The next two technology categories (in situ biological treatment for EXPs-contaminated groundwater and chemical treatment for EXPs-contaminated soil) also have similar probability-weighted payoffs, which are significantly larger than those for the fifth and sixth ranked technologies. It is interesting to note that chemical treatment for EXPs-contaminated soil, which is a backup technology category, has a larger probability-weighted payoff than the preferred technology categories for three of the contamination categories. This result emphasizes the dominant role of EXPs-contaminated soil treatment in the DA IRP. Developing a second alternative technology to ensure that EXPs-contaminated soil treatment costs are reduced appears to be a better investment than developing alternative treatment technologies from the preferred technology categories for HMs-contaminated soil and groundwater and VOCs-contaminated soil.

The fifth ranked technology category (onsite physical treatment for EXPs-contaminated groundwater) is also a backup technology. Even so, it has twice as large a probability-weighted payoff as the onsite chemical treatment for HMs-contaminated groundwater, the sixth ranked technology. Again, reducing costs associated with EXPs contamination is a high priority for the DA IRP.

The remaining technology categories (6 through 12) are all roughly equivalent based on probability-weighted payoff. However, physical treatment for HMs-contaminated soil and biological treatment for VOCs-contaminated soil have higher potential payoffs and are therefore considered the seventh and eighth priorities. The remaining four technology categories are all backup technologies and are essentially indistinguishable in this analysis.

6.4.2 R&D Investment Strategies

As noted in Section 6.1, the current USATHAMA R&D funding level will allow development of four technology categories, assuming that the average cost for each is similar to previous USATHAMA experience. For this analysis, it was assumed that incremental R&D funding would allow proportionately more technologies to be developed. Therefore, 150%, 200%, and 300% of current funding would allow development of 6, 8, and 12 technology categories, respectively. R&D investment strategies for these levels of USATHAMA R&D can be formulated from the R&D priority rankings on Table 6.3.

Table 6.4 shows the R&D strategies for these four different levels of funding. Also shown on the table are the incremental probability-weighted payoff and incremental potential payoff as additional R&D funding is added.

Table 6.4 shows that developing technologies from the first four technology categories could save as much as $1600 million on the portion of the DA IRP included in the estimates for this study. (As noted in Sections 3.2 and 4.2, some additional sources of contamination were not quantified and included in this study, so remedial action requirements and potential savings may be larger than estimated here.) The range of "expected" or probability-weighted payoffs for this set of investments is approximately $40 to $340 million. These estimates indicate that the current level of USATHAMA R&D funding for technology development in support of the DA IRP should, assuming typical or average success for these types of investment, result in between a 3:1 and 20:1 payoff (saving:investment), and current R&D funding could result in a 100:1 payoff.

With 50% additional funding (approximately $7 to $8 million), technologies from two additional categories could be developed, increasing potential DA IRP cost reductions as much as $140 million (again, more could be saved if remedial actions are higher than estimated in this report); the probability-weighted payoff for this incremental investment ranges from $5 to $65 million. If average success for these investments were realized, the payoff would be between 1:1 and 10:1 and could be as high as 20:1. These payoffs are lower than the payoffs for the base funding, as is expected considering that they correspond to investment in lower priority technology categories.

TABLE 6.4. R&D Investment Strategies and Payoffs by Funding Level Increments

Funding Level	Technology Categories	Incremental Probability-Weighted Payoff (10^6)	Incremental Potential Payoff (10^6)(a)
Current Funding	In Situ Biological Technology for VOCs-Contaminated Groundwater Biological Technology for EXPs-Contaminated Soil In Situ Biological Technology for EXPs-Contaminated Groundwater Chemical Technology for EXPs-Contaminated Soil	~$40 to $340	~$200 to $1600
+ 50%	Onsite Physical Technology for EXPs-Contaminated Groundwater Onsite Chemical Technology for HMs-Contaminated Groundwater	~$5 to $65	~$10 to $140
+ 50%	Physical Technology for HMs-Contaminated Soil Biological Technology for VOCs-Contaminated Soil	~$8 to $20	~$40 to $65
+ 100%	Onsite Biological Technology for HMs-Contaminated Groundwater Onsite Biological Technology for VOCs-Contaminated Groundwater Thermal Technology for VOCs-Contaminated Soil Thermal Technology for HMs-Contaminated Soil	~$9 to $46	$0

(a) Estimated maximum payoff for current funding level and for increasing funding increments.

An additional 50% funding (a total of 100% more) adds slightly less ($40 to $65 million) to the potential estimated DA IRP cost reduction and slightly less to the probability-weighted payoff ($8 to $20 million). These

additional cost reductions correspond to expected payoffs on this incremental investment of between 1:1 and 3:1 and potentially to a payoff as high as 10:1. Again, incremental investments lead to less incremental savings, but these savings are still commensurate with the required investment.

If another 100% incremental R&D funding is assumed, the last four backup technology categories can be developed. While the additional 100% does not increase the potential cost savings, as "insurance" it would increase the probability-weighted payoff for the R&D program $9 to $46 million. This corresponds to an expected payoff of between less than one (incremental investment not recovered) and 3:1.

7.0 REFERENCES

Anderson, A. W. 1988. Installation Restoration Program Status Report - 31 July 1988. U.S. Army Toxic and Hazardous Materials Agency, Edgewood, Maryland.

Beaudet, B. A., J. W. Vinzant, L. J. Bilello, J. D. Crane, and R. A. Pisigan. 1983a. Development of Optimum Treatment Systems for Industrial Wastewater Lagoons, Task 3 Final Report, Volume I. Report No. DRXTH-TE-CR-83232, Environmental Science and Engineering, Inc., Gainesville, Florida.

Beaudet, B. A., J. W. Vinzant, L. J. Bilello, J. D. Crane, and R. A. Pisigan. 1983b. Development of Optimum Treatment Systems For Industrial Wastewater Lagoons, Task 3 Final Report, Volume II. Report No. DRXTH-TH-CR-83233, Environmental Science and Engineering, Inc., Gainesville, Florida.

Beaudet, B. A., J. W. Vinzant, L. J. Bilello, J. D. Crane, and R. A. Pisigan. 1983c. Development of Optimum Treatment Systems for Industrial Wastewater Lagoons, Task 3 Final Report, Volume III. Report DRXTH-TE-CR-83234, Environmental Science and Engineering, Inc., Gainsville, Florida.

Biggs, R. K., K. Klink, and J. Crenca. 1989. "The Cost of Remedial Actions (CORA) Model: Overview and Applications." In Proceedings of HAZMACON 89, Hazardous Materials Management Conference and Exhibit, pp. 327-335. Association of Bay Area Governments (ABAG). Oakland, California.

Bove, L. J., C. L. Cundal, W. P. Lambert, J. F. Martino, and P. J. Marks. 1983. Removal of Contaminants from Soil. Phase I: Identification and Evaluation of Technologies. Report No. DRXTH-TE-CR-83249, Roy F. Weston, Inc., West Chester, Pennsylvania.

Bove, L. J., W. P. Lambert, L. Y. H. Lin, D. E. Sullivan, and P. J. Marks. 1984. Development of New Technology for the Removal of Contaminants from Groundwater - Identification and Assessment of Treatment Concepts. Report No. DRXTH-TE-CR-84270, Roy F. Weston, Inc., West Chester, Pennsylvania.

Boyd, D. W., and S. G. Regulinski. 1979. Characterizing Uncertainty in Technology Cost and Performance. Decision Focus Inc., Palo Alto, California.

Coia, M. F., M. H. Corbin, A. L. Lenthe, P. J. Marks, and A. A. Metry. 1983. Task 3, Guidelines for In-Place Closure of Dry Lagoons, Volume I Regulatory Requirements. Report No. DRXTH-TE-CR-83204, Roy F. Weston, Inc., West Chester, Pennsylvania.

Defense Environmental Restoration Account (DERA). 1988. Annual Report to Congress for Fiscal Year 1987. Office of the Deputy Assistant Secretary of Defense (Environment), Washington, D.C.

Electric Power Research Institute (EPRI). 1979. Uncertainty Methods in Comparing Power Plants. EPRI-FFAS-1048, Palo Alto, California.

Frank, J. F., M. E. Dinkel, and D. M. Chari. 1987. "Use of Mobile Incineration to Remediate the Lenz Oil Site." In Superfund '87, Proceedings of the 8th National Conference, pp. 459-464. The Hazardous Materials Control Research Institute, Washington, D.C.

Freeze, R. A., and J. A. Cherry. 1979. Groundwater. Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Holloway, C. A. 1979. Decision Making Under Uncertainty: Models and Choices. Prentice Hall, Inc., Englewood Cliffs, New Jersey.

Lyman, W. J. 1982. Handbook of Chemical Property Estimation. McGraw Hill, Inc., New York, New York.

Nielson, R. K., A. K. Cohen, and P. A. Spaine. 1988. "Low Temperature Thermal Treatment of Volatile Organic Compounds." In Proceedings for the 13th Annual Environmental Quality R&D Symposium, pp. 187-202. U.S. Toxic and Hazardous Materials Agency, Aberdeen Proving Grounds, Maryland.

Offutt, C. K. 1988. "The Impact of Land Disposal Restrictions on Superfund Response Actions." In Superfund '88, Proceedings of the 9th Annual Conference. The Hazardous Materials Control Research Institute, Washington D.C.

Oster, C. C., P. Connell, and N. C. Wenck. 1988. "Vacuum Extraction of Volatile Organic Compounds from Soil." In Proceedings for the 13th Annual Environmental Quality R&D Symposium, pp. 179-186. U.S. Toxic and Hazardous Materials Agency, Aberdeen Proving Grounds, Maryland.

Science Applications International Corporation (SAIC). 1988. Stringfellow Hazardous Waste Site Feasibility Study Draft Final Report. California Department of Health Services, Toxic Substances Control Division, Sacramento, California.

Turkeltaub, R. B., and C. D. Wiehl. 1988. "U.S. Army Installation Restoration Incineration Program at Cornhusker and Louisiana Army Ammunition Plants." In Superfund '88, Proceedings of the 9th National Conference, pp. 569-574. The Hazardous Materials Control Research Institute, Washington, D.C.

Turkeltaub, R. B., and C. D. Wiehl. 1989. "Cleaning Up Explosives at Army Munitions Plants Using Incineration." Hazardous Materials 2(4):26-34.

Williams, R. T., P. S. Ziengenfuss, G. B. Mohrman, and W. E. Sisk. 1988. "Composting of Explosive Contaminated Sediments." In Proceedings for the 13th Annual Environmental Quality R&D Symposium, pp. 130-139. U.S. Toxic and Hazardous Materials Agency, Aberdeen Proving Grounds, Maryland.

U.S. Environmental Protection Agency (EPA). 1988. Cost of Remedial Action Model Users Manual, Version 2.1. Prepared by CH2M Hill for the U.S. Evironmental Protection Agency Office of Solid Waste And Emergency Response, Washington, D.C.

APPENDIX A

CALCULATION OF CONTAMINATED-SOIL VOLUMES

APPENDIX A

CALCULATION OF CONTAMINATED-SOIL VOLUMES

This appendix describes how the volumes of contaminated soil presented in Section 3.1 were calculated. The objective of estimating the volumes of soil contaminated with explosives (EXPs), heavy metals (HMs), and volatile organic compounds (VOCs) at Army installations was to develop a relative measure of the Army's hazardous waste problem. The order-of-magnitude contaminated soil volumes that resulted were used with cost data to determine the likely "targets" for spending R&D funds.

A.1 CALCULATIONAL APPROACH

Comprehensive contaminated soil data for the 1391 active and inactive Army installations (DERA 1987) are not available. Therefore, the approach used in this study to estimate the total volume of contaminated soil at Army installations was to identify the major sources of contaminated soil and assess the limited data currently available. (It was beyond the scope of this study to generate a comprehensive data base of contaminated soil sites at all Army installations).

The major sources of contaminated soil include wastewater lagoons (including trenches, ditches and impoundments), soil around production facilities, and burning grounds. Limited data were available on wastewater lagoons, trenches, ditches, and impoundments used to dispose of contaminated wastewater (Coia et al. 1983 and Beaudet et al. 1983a,b,c). Sources of data to estimate the volume of contaminated soil around production facilities and in burning grounds were not available.

The WESTON report (Coia et al. 1983) was used as the primary source of information for determining the number of installations with contaminated lagoons and the number of contaminated lagoons at each of the installations. The volumes of contaminated soil at each installation were calculated by

multiplying the number of contaminated lagoons by the volume of contaminated soil associated with the lagoons. WESTON surveyed 41 installations associated with munitions production, plating and metal finishing, and other industrial operations. Of the 41 Army installations surveyed in that report, 39 have wastewater lagoons contaminated with a combination of EXPs, VOCs, and HMs.

Comprehensive site data were not available from all of the 41 installations surveyed by WESTON, therefore a measure of a "standard lagoon" was devised by WESTON, ESE, and USATHAMA as a means to present consistent information (there is not an actual "standard lagoon"). (The dimensions of a "standard lagoon" are 100-ft by 150-ft.) For example, at Cornhusker Army Ammunition Plant, the installation data in the Appendix of the WESTON report indicated 9 leaching pits, 47 cesspools, 3 holding ponds, and 1 acid waste pond. This information was reported in the text as 9 "standard lagoons." For this study, the potential contaminated soil volumes at each installation were calculated from the standard lagoon dimensions if other site specific data were not available. Most of the site specific data were found in the ESE report (Beaudet et al 1983a). In a few cases where there was significant differences between the data presented in the WESTON and ESE reports, the appropriate USATHAMA project officers were consulted.

The volume of contaminated soil associated with a lagoon was calculated using the equation for an obelisk and the assumptions that 1) for wastewater lagoons contaminated with EXPs and HMs, approximately 6 ft of soil around each lagoon was contaminated (see Figure A.1), and 2) for wastewater lagoons contaminated with VOCs, approximately 15 ft of soil was contaminated (see Figure A.2). Six feet of soil around EXPs-contaminated lagoons was chosen

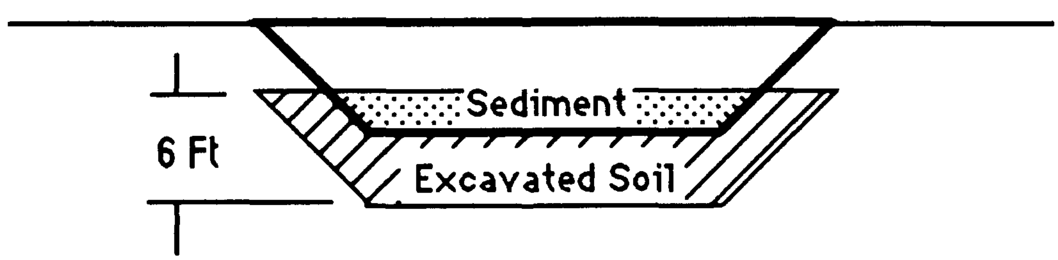

FIGURE A.1. Schematic of the Volume of Contaminated Soil Associated with a Lagoon Contaminated with Explosives and Heavy Metals

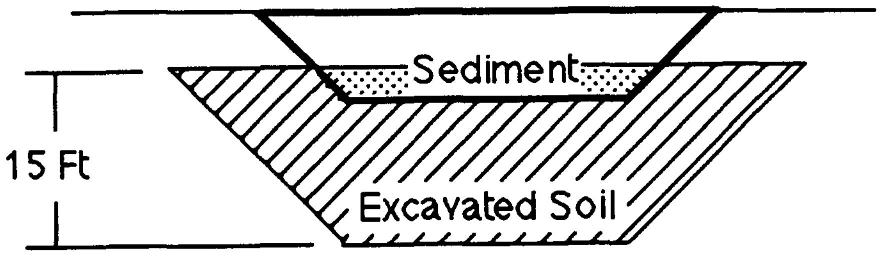

FIGURE A.2. Schematic of the Volume of Contaminated Soil Associated with a Lagoon Contaminated with VOCs

because it is consistent with current Army IRP experiences. Six feet was chosen for HMs-contaminated lagoons because metals have a tendency to adsorb to soils and tend not to travel far through the vadose zone. Fifteen feet was chosen for VOCs-contaminated lagoons for two reasons: 1) VOCs have higher adsorptivity coefficients; they have a tendency to move farther through the vadose zone than EXPs and HMs, and 2) 15 ft is a reasonable maximum excavation depth.

The actual width and depth of contaminated soil to be treated at each site will be negotiated with the appropriate regulatory agencies, and is unknown at this time. Therefore, a range of ± 20% was included in the estimate of the contaminated soil volumes. A summary of the calculated soil volumes at each installation is presented in Table A.1.

TABLE A.1. Calculated Potential Contaminated Soil Volumes from Wastewater Lagoons, tons[a]

Installation	Contamination Category: Explosives	Heavy Metals	Volatile Organics
Alabama AAP	0	0	45,000
Anniston AD	18,000	25,000	18,000
Badger AAP	0	0	0
Blue Grass AD	18,000	15,000	0
Cornhusker AAP	42,000	0	0
Ft Wingate AD	18,000	0	0
Hawthorne AAP	115,000	0	0
Holston AAP	0	0	9,000
Indiana AAP	18,000	0	0
Iowa AAP	9,000	5,000	0
Joliet AAP	18,000	0	0
Kansas AAP	54,000	0	0
Lake City AAP	18,000	80,000	0
Letterkenny AD	0	5,000	9,000
Lone Star AAP	125,000	9,000	0
Longhorn AAP	25,000	0	5,000
Louisiana AAP	120,000	5,000	23,000
McAlester AAP	65,000	0	0
Milan AAP	70,000	0	0
Navajo AD	50,000	0	0
Newport AAP	30,000	0	0
Picatinny Ar	9,000	5,000	0
Pine Bluff Ar	0	0	0
Pueblo AD	10,000	5,000	0
Radford AAP	9,000	0	0
Ravena AAP	20,000	0	0
Red River AD	0	5,000	0
Redstone Ar	0	5,000	0
Riverbank AAP	0	18,000	0
Sacramento AD	0	23,000	0
Savanna AD	30,000	0	0
Seneca AD	5,000	0	0
Sharpe AD	0	0	0
Sunflower AAP	15,000	0	0
Tobyhanna AD	0	0	0
Tooele AD	25,000	5,000	0
Twin Cities AAP	15,000	0	9,000
Umatilla AD	60,000	0	0
Volunteer AAP	75,000	0	0
White Sands MR	0	0	62,000
TOTAL, tons	~1,090,000	~210,000	~180,000

(a) Based on information found in Coia et al. 1983 and Beaudet et al. 1983.

A.2 REFERENCES

Beaudet, B. A., J. W. Vinzant, L. J. Bilello, J. D. Crane, and R. A. Pisigan. 1983a. Development of Optimum Treatment Systems for Industrial Wastewater Lagoons, Task 3 Final Report, Volume I. Report No. DRXTH-TE-CR-83232, Environmental Science and Engineering, Inc., Gainesville, Florida.

Beaudet, B. A., J. W. Vinzant, L. J. Bilello, J. D. Crane, and R. A. Pisigan. 1983b. Development of Optimum Treatment Systems For Industrial Wastewater Lagoons, Task 3 Final Report, Volume II. Report No. DRXTH-TH-CR-83233, Environmental Science and Engineering, Inc., Gainesville, Florida.

Beaudet, B. A., J. W. Vinzant, L. J. Bilello, J. D. Crane, and R. A. Pisigan. 1983c. Development of Optimum Treatment Systems for Industrial Wastewater Lagoons, Task 3 Final Report, Volume III. Report DRXTH-TE-CR-83234, Environmental Science and Engineering, Inc., Gainsville, Florida.

Coia, M. F., M. H. Corbin, A. L. Lenthe, P. J. Marks, and A. A. Metry. 1983. Task 3, Guidelines for In-Place Closure of Dry Lagoons, Volume I Regulatory Requirements. Report No. DRXTH-TE-CR-83204, Roy F. Weston, Inc., West Chester, Pennsylvania.

Defense Environmental Restoration Account (DERA). 1988. Annual Report to Congress for Fiscal Year 1987. Office of the Deputy Assistant Secretary of Defense (Environment), Washington, D.C.

APPENDIX B

<u>SUPPORT DATA FOR RANKING TECHNOLOGY CATEGORIES</u>

APPENDIX B

SUPPORT DATA FOR RANKING TECHNOLOGY CATEGORIES

The unit cost targets and potential payoffs discussed in Section 3 and 4 were used with a ranking of the technology categories (Section 5) to help USATHAMA prioritize their R&D investments (the objective of this study). The worksheets used to rank the technology categories are discussed in this appendix.

B.1 APPROACH

The basis for ranking the technology categories was their likelihood of successfully meeting the target unit cost for a particular remedial action category. Several steps are performed in ranking the technology categories. The steps are to 1) generate a list of feasible treatment technologies for each waste category (e.g., EXPs-contaminated soil and HMs-contaminated soil), 2) identify the estimated unit cost of each technology, 3) rank the technology categories based on estimated unit cost and stage of development (technologies with estimated unit costs near the target but in the bench-scale stage of development are assumed to be less likely to actually meet target costs than technologies in the pilot- and full-scale stage), and 4) assign a value to the qualitative rankings.

The lists of feasible treatment technologies for each waste category (the first step outlined in the approach) are presented in Tables B.1 through B.6. These tables were generated using USATHAMA technology evaluation studies (Bove et al. 1983 and 1984) and supplemented with representative technologies that were developed after the studies were performed. The lists of treatment technologies are not comprehensive (that was beyond the scope of this study); instead, they represent the type of technologies that are identified in the literature.

Unit costs were estimated (and presented in Tables B.1 through B.6) for each technology listed based on information from the open literature and from

vendors. The unit cost data were used to generate a table of technologies that could potentially meet the target unit costs discussed in Sections 3 and 4. The list of "potential" technologies is presented in Table B.7.

The technology categories were ranked (using the list of potential technologies) on the basis of two criteria: 1) the number of technologies that could potentially meet the unit cost requirements and 2) the stage of development of each technology. When the technology categories were evaluated on these criteria, they fell into three distinct levels of potential for yielding a technology that can meet the relevant unit cost target (high, medium, and low).

Ranges of quantitative values were assigned to the qualitative rankings discussed above. These values, expressed in percentages, represent the likelihood that a category could produce a technology that can meet the target unit cost for a particular application. THese values were used to develop R&D funding strategies for alternative R&D funding levels (see Section 6). Results from the ranking process are discussed in Section 5.

TABLE B.1. Explosives-Contaminated Soil Treatment Technologies

Treatment Category	Treatment Technologies	Development/Feasibility Status	Cost-Range ($/Ton)	Cost-Range Reference	Comments
Physical/ Chemical	Secure Landfill	Full-scale; not applicable to EXPs.	44 to 190	7, 23	Isolation/disposal treatment.
	Geologic Isolation	Under development for radioactive waste; not applicable to EXPs.	Unavailable		Isolation/disposal treatment.
	Slurry Wall	Full-scale.	NA	7	Temporary isolation method. $2 to $3.5/ft^2$.
	Solidification/Stabilization	Full-scale; not applicable to EXPs.	20 to 200	21, 8	Isolation treatment. Disposal required.
	Soil Organic Solvent Extraction - Onsite	Full-scale; demonstrated for VOCs. Unproven for EXPs, but likely feasible.	100 to 500	(a)	Separation treatment. Secondary solid waste; 20 to 50 soil vol%, residue from solvent recovery. Solvent may contaminate soil.
	- In Situ	Unproven at pilot-scale. Not feasible for low concentrations.	Unavailable		Separation treatment. Residue from solvent recovery. Solvent may contaminate soil and groundwater.
	Soil Washing (aqueous extraction) - Onsite	Full-scale, unproven for EXPs, but likely feasible.	100 to 200	16	Separation treatment. Secondary solid waste 20 to 50 soil vol%, contaminated wastewater.
	- In Situ Soil Flushing	Unproven at pilot-scale. Not effective without surfactant.	50 to 150	15	Separation treatment. Wastewater produced. Less effective for heterogeneous soils. May contaminate groundwater.
	Soil Gas Extraction (Air/Steam)	Demonstrated at full-scale for VOCs. Unproven for EXPs.	25 to 100	13	Separation treatment. Contaminated gas must be treated.
	Chemical Oxidation (Includes Fenton's reagent, free radical oxidation)	Generally unproven for contaminated soils. Fenton's reagent tested with explosives in USATHAMA project.	NA	10, 14, 2, 8	Destroys organics - may leave secondary products. Includes ozone, H_2O_2 (with catalyst) and $KMnO_4$. Applicable to wastewater - may oxidize solids. Ozone and H_2O_2 may be assisted by UV or ultrasonics.
	In Situ Surfactant Complexing	Bench-scale; evaluated for EXPs.			Precipitates EXPs. Complex may be more hazardous. Large quantities of surfactant required.
	Base-Initiated Reduction	Bench-scale; under development by USATHAMA for EXPs.	Unavailable		Destroys EXPs. Requires pretreatment to pH 10, plus surfactants.

TABLE B.1. (contd)

Treatment Category	Treatment Technologies	Development/Feasibility Status	Cost Range ($/Ton)	Cost Range Reference	Comments
Thermal	Incineration	Full-scale, many configurations; demonstrated for EXPs in rotary kiln.	200 to 600	7 (b)	Destroys organic.
	Plasma Torch	Pilot-scale.	300 to 105	6, 20	Destroys organics. Site demonstration planned for 1990.
	Microwave Plasma Detoxification	Not tested; not practical for large volumes.	≤600	9	Destroys organics.
	Low-Temperature Thermal Stripping	Full-scale; not tested for EXPs.	80 to 350	7, 11, 20	Destroys organics. Soil heating ranges from 300 to 850°F.
	Low-Temperature Thermal Decomposition	Under development by USATHAMA for EXPs, based on data for pure explosives.	Unavailable		Destroys explosives. Moderate pressure (350 psi) required.
	In Situ Vitrification (ISV)	Theoretical studies performed.	270 to 400	3	Separates and/or destroys organics. Fume hood captures gases to further treat.
	In Situ Heating (ISH)	Unproven; probably not feasible.	50 to 120	17	Destroys some organics.
	Molten Glass	No tests performed.	350	12	Destroys organics; isolates solids in glass.
	Supercritical Water Oxidation	Unproven for contaminated soils.	NA		Destroys organics. Cannot pump solids to high pressure (3000 psi) required.
	Wet Air Oxidation	Unproven for contaminated soils.	NA		Incompletely destroys organics. Liquid effluent must be further treated. Moderate to high pressure required. Waste must be pumpable.
	Catalytic Destruction	Bench-scale; not feasible for soils.	NA	1	Destroys organics in aqueous solution. More applicable to wastewater, pumpable sludge containing 1% to 10% organics. High pressure (3000 psi) required.
Biological	Composting	Pilot-scale.	100 to 300	(b)	Destroys organics. Water insoluble organics difficult to degrade.
	Bioreactors	Full-scale.	37 to 400	12, 20	Destroys organics. Water insoluble organics difficult to degrade. Generates sludge.
	Landfarming	Full-scale for organics; applicability for EXPs unproven.	37 to 59	22	Destroys organics. Water insoluble organics difficult to degrade.

(a) 1987 draft report on technology needs for remediating mixed waste and hazardous waste sites, Pacific Northwest Laboratory, Richland, Washington.
(b) Review of Superfund Records of Decision.

TABLE B.2. Heavy Metals-Contaminated Soil Developmental Treatment Technologies

Treatment Category	Treatment Technologies	Development/Feasibility Status	Cost Range ($/Ton)	Cost Range Reference	Comments
Physical/ Chemical	Geologic Isolation	Under development for radioactive waste.	Unavailable		Isolation/disposal treatment.
	Stabilization/solidification	Full-scale.	20 to 200	8, 21	Isolation treatment. Disposal required. Stabilization, microencapsulation include several types of organic and inorganic matrixes. Waste volume increases 30% to 40%. Microencapsulation uses high-density polyethylene around rigid containers.
	Slurry Wall	Full-scale.	NA	7	Temporary isolation method. \$2 to \$3.5/ft^2.
	High Gradient Magnetic Separation	Full-scale, potentially feasible for soil.	1 to 7	5	Solid separation process using 10 to 15 vol% slurry concentrations. Solids should be $\leq 100\mu$. Quantity of contaminated solids needing further treatment variable. Costs based on \$1 to \$5/1000 gal assuming 15 vol%, 1.5 specific gravity solids.
	In-Place Stabilization	Pilot-scale.	Unavailable		Isolation treatment. Mixing accomplished using a backhoe. Waste volume increases.
	Soil Organic Solvent Extraction				
	- Onsite	Pilot-scale, not applicable to metals.	NA		
	- In Situ	Not applicable to metals.	NA		
	Soil Washing (aqueous solvent)				
	- Onsite	Pilot-scale (60% to 90% removal).	100 to 200	16	Separation treatment. PH adjustment or surfactants usually required. Secondary solid waste produced (20 to 50 vol%). Wastewater requires treatment.
	- In Situ	Ready for use, effective for spills.	50 to 150	15	Separation treatment. Wastewater produced. Less effective for heterogeneous soils. May contaminate groundwater.

TABLE B.2. (contd)

Treatment Category	Treatment Technologies	Development/Feasibility Status	Cost Range ($/Ton)	Reference	Comments
Thermal	In Situ Vitrification (ISV)	Theoretical studies performed.	270 to 400	3	Isolation/disposal treatment.
	Plasma Torch	Pilot-scale.	300 to 105	6, 20	Isolation treatment. Disposal required. Volatile metals such as Hg may need removal from flue gas.
	Molten Glass	No tests performed.	350	12	Isolation treatment. Disposal required. Volatile metals such as Hg may need removal from flue gas.
	Incineration	Full-scale.	200 to 600	18 (a)	Isolation treatment. 101 out of 104 met extraction procedure toxicity (EPTox).
	Supercritical oxidation	Not applicable to soils or metal removal.	NA	7	
Biological	Bioreactor - bioaccumulation, vegetative uptake	Not applicable to soils.	NA		Separation treatment. Destruction or isolation not achieved; requires further treatment of soil and/or plant matter.

(a) Review of Superfund Records of Decision.

TABLE B.3. Volatile Organic Compounds-Contaminated Soil Treatment Technologies

Treatment Category	Treatment Technologies	Development/Feasibility Status	Cost Range ($/Ton)	Cost Range Reference	Comments
Physical/ Chemical	Secure Landfill	Full-scale.	44 to 190	7, 23	Isolation/disposal treatment.
	Geologic Isolation	Under development for radioactive waste; not applicable to VOCs.	Unavailable		Isolation/disposal treatment.
	Slurry Wall	Full-scale.	NA	7	Temporary isolation method. \$2 to \$3.5/ft^2.
	Solidification/Stabilization	Full-scale.	20 to 200	8, 21	Isolation treatment. Disposal required.
	Soil Organic Solvent Extraction - Onsite	Full-scale.	100 to 500	(a)	Separation treatment. Secondary solid waste 20 to 50 soil vol%, residue from solvent recovery. Solvent may contaminate soil.
	- In Situ	Not feasible for low concentration.	Unavailable		Separation Treatment. Residue from solvent recovery. Solvent may contaminant soil and groundwater.
	Soil Washing (aqueous extraction) - Onsite	Full-scale.	100 to 200	16	Separation treatment. Secondary solid waste 20 to 50 soil vol%, contaminated wastewater.
	- In Situ Soil Flushing	Not effective without surfactant.	50 to 150	15	Separation treatment. Wastewater produced. Less effective for heterogeneous soils. May contaminate groundwater.
	Soil Gas Extraction (Air/Steam)	Full/pilot-scale.	25 to 100	13	Separation treatment. Contaminated gas must be treated.
	Chemical Oxidation (includes Fenton's Reagent, free radical oxidation)	Generally unproven for contaminated soils.	NA	2, 10, 14	Destroys organics - may leave secondary products. Includes ozone, H_2O_2 (with catalyst) and $KMnO_4$. More applicable to wastewater - may oxidize solids. Ozone and H_2O_2 may be assisted by UV or ultrasonics.
	In Situ Surfactant Complexing	Not tested on VOCs. Probably not feasible for many VOCs.			Precipitates EXPs. Complex may be more hazardous. Large quantities of surfactant required.
	Base-Initiated Reduction	Bench-scale; under development by USATHAMA for EXPs. Probably not applicable to VOCs.	Unavailable		Destroys explosives. Requires pretreatment to pH 10, plus surfactants.

TABLE B.3. (contd)

Treatment Category	Treatment Technologies	Development/Feasibility Status	Cost Range ($/Ton)	Reference	Comments
Thermal	Incineration	Full-scale; many configurations.	200 to 600	7 (b)	Destroys organics.
	Plasma Torch	Pilot-scale.	300 to 105	6, 20	Destroys organics. Site demonstration planned in 1990.
	Microwave Plasma Detoxification	No tests; not practical for large volumes.	≤600	9	Destroys organics.
	Low-Temperature Thermal Stripping	Full-scale; not tested for EXPs.	80 to 350	7, 11, 20	Destroys organics. Soil heating ranges from 300 to 850°F.
	Low-Temperature Thermal Decomposition	Under development by USATHAMA for EXPs. Not applicable to VOCs.	Unavailable		Destroys explosives. Moderate pressure (350 psi) required.
	In Situ Vitrification (ISV)	Pilot-scale.	270 to 400	3	Separates and/or destroys organics. Fume hood captures gases to treat further.
	In Situ Heating (ISH)	Bench-scale.	50 to 120	17	Destroys some organics.
	Molten Glass	Bench-scale.	350	12	Destroys organics; isolates solids in glass.
	Supercritical Water Oxidation	Unproven for contaminated soils.	NA		Destroys organics. Cannot pump solids to high pressure (3000 psi) required.
	Wet Air Oxidation	Unproven for contaminated soils.	NA		Incompletely destroys organics. Liquid effluent must be further treated. Moderate to high pressure required. Waste must be pumpable.
	Catalytic Destruction	Bench-scale, not proven for EXPs.	NA	1	Destroys organics. More applicable to wastewater; pumpable sludge contains 1% to 10% organics. High pressure (3000 psi) required.
Biological	Composting	Pilot-scale	100 to 300	(b)	Destroys organics. Water insoluble organics difficult to degrade. VOCs may be stripped into air.
	Bioreactors	Full-scale	37 to 400	12, 20	Destroys organics. Water insoluble organics difficult to degrade. Generates sludge.
	Landfarming	Full-scale	37 to 59	22	Destroys organics. Water insoluble organics difficult to degrade. VOCs may be stripped into air.

(a) 1987 draft report on technology needs for remediating mixed waste and hazardous waste sites, Pacific Northwest Laboratory, Richland, Washington.
(b) Review of Superfund Records of Decision.

TABLE B.4. Explosives-Contaminated Groundwater Developmental Treatment Technologies

Treatment Category	Treatment Technologies	Development/Feasibility Status	Cost Range ($/Ton)	Reference	Comments
Physical/ Chemical	Resin Adsorption	Full/pilot-scale. Proven for EXPs.	$\leq$1 to 20	2, 5	Separation treatment. Concentrated regeneration stream needs treatment.
	Carbon Adsorption	Full-scale.	$\leq$1 to 20	5	Separation treatment. Carbon cannot be regenerated and must be disposed.
	Reverse Osmosis/Membrane Sep.	Should be applicable.	1 to 20	7, 15, 24	Separation treatment. Concentrated waste stream must be further treated.
	Chemical Oxidation (Free Radical Oxidation)	Full-scale.	$\leq$1 to 4	2, 10, 14	Destroys organic - may leave secondary products. Includes ozone, H_2O_2 (with catalyst) and $KMnO_4$. Applicable to wastewater - May oxidize solids. Ozone and H_2O_2 may be assisted by UV or ultrasonics.
	Air/Steam Stripping	Full-scale; unproven for EXPs.	$\leq$1 to 24	2, 7, 14	Separation treatment. Contaminated gas must be treated.
	Distillation/Evaporation Systems	Full-scale; unproven for EXPs.	$\leq$3 to 10	2, 7	Separation treatment. Residual bottoms, and overhead vapor may require further treatment.
	Organic Solvent Extraction	Full-scale.	$\leq$5 to 30	2	Separation treatment. Costs generally include treatment to recover solvent from treated water prior to discharge using air/steam stripping.
	In Situ Surfactant Complexing	Bench-scale. Evaluated for EXPs. Probably not applicable to VOCs.	NA		Precipitates EXPs. Complex may be more hazardous. Large quantities of surfactant required. Does not treat EXPs degradation compounds.
	Base-Initiated Reduction	Bench-scale; under development by USATHAMA for EXPs. Probably not applicable to VOCs.	NA		
	Freeze Crystallization	Pilot-scale tests have been reported for arsenal redwater.	20 to 100	7, 10, 20	Separation treatment. Concentrated aqueous waste stream needs further treatment. Generally removes all impurities equally well.
	Catalytic Destruction	Bench-scale. Not feasible for soils.	20 to 30	1	Destroys organics. More applicable to wastewater, pumpable sludge containing 1% to 10% organics. High pressure (3000 psi) required.

TABLE B.4. (contd)

Treatment Category	Treatment Technologies	Development/Feasibility Status	Cost Range ($/Ton)	Cost Range Reference	Comments
Thermal	Supercritical Water Oxidation	Full-scale; unproven for EXPs.	170 to 1000	7	Destroys organics including EXPs.
	Wet Air Oxidation	Full-scale; unproven for EXPs.	60 to 260	2, 20	Incompletely destroys organics. Liquid effluent must be further treated. Moderate to high pressure required. Waste must be pumpable.
Biological	Biological Activated Carbon	Full-scale.	6 to 31	20	Destroys organics. Tolerates higher concentrations of organics. Must thermally regenerate carbon.
	Bioreactors	Full-scale. Unproven for EXPs but probably feasible.	5 to 10	(a)	Destroys organics. Generates sludge.
	In Situ Biotreatment	Bench/pilot-scale.	125	19	Destroys organics. Very limited data for organics.
	Enzyme Destruction	Lab-scale.	Unavailable	7	Destroys specific compounds. Generates secondary products. Each enzyme effective for single compound.

(a) Vendor information from Chemical Waste Management, Inc., Newark, California; Casmalia Resources, Santa Barbara, California; Environsafe Service of Idaho, Grand View, Idaho.

TABLE B.5. Heavy Metals-Contaminated Groundwater Developmental Treatment Technologies

Treatment Category	Treatment Technologies	Development/Feasibility Status	Cost Range ($/Ton)	Cost Range Reference	Comments
Physical/ Chemical	Ion Exchange	Full-scale.	1 to 10	7	Separation treatment; concentrated regeneration solution needs further treatment. Spent resin needs further treatment.
	Chemical Precipitation	Full-scale.	≤1 to 6	5	Separation treatment. Solid residue ma need neutralization, dewatering, solidification/stabilization. Treated water may need further treatment, e.g., ion exchange.
	Electrochemical Recovery Process	Full-scale.	≤1 to 2	5, 20	Separation treatment. Metals recovered as a solid.
	Membrane Separation (includes reverse osmosis, ultrafiltration)	Full-scale.	1 to 20	7, 15, 24	Separation treatment. Concentrated aqueous waste stream needs further treatment.
	Freeze Crystallization	Full-scale.	20 to 100	7, 10, 20	Separation treatment. Concentrated aqueous waste stream needs further treatment. Generally removes all impurities equally well.
	Activated Carbon/Adsorbents	Full-scale.	Unavailable		Separation treatment. Concentrated Regeneration solution needs further treatment. Same as ion exchange but uses materials other than resins or zeolites.
	Organic Solvent Extraction (liquid-ion exchange)	Full-scale.	3 to 5	5	Separation treatment. Treated waste will contain trace amounts of solvent. Solution to regenerate solvent will need further treatment.
	Evaporation Systems	Full-scale.	15 to 20	5	Separation treatment. Concentrated sludge needs further treatment.
	Chemical Oxidation	Full-scale; generally not applicable to metals.	NA		Will raise oxidation potential of dissolved metals which can affect subsequent treatment.
	Chemical Reduction	Full-scale.	150 to 250	5, 7	Separation treatment/pretreatment. Commonly used to reduce Cr(VI) to Cr(III) as a pretreatment to precipitation. Can be used to remove Pb, Sn, and Hg from waste water.

TABLE B.5. (contd)

Treatment Category	Treatment Technologies	Development/Feasibility Status	Cost Range ($/Ton)	Cost Range Reference	Comments
	Organic-Metal Precipitation (includes xanthates and carbamates)	Bench/pilot-scale.	Unavailable		Separation treatment. Sludge requires further treatment. Hazardous gases may be required to regenerate organic reactant.
	High Gradient Magnetic Separation	Full-scale; used in conjunction with ferrous sulfate precipitation seeded onto a suspension of magnitite.	≤1 est.	5	Separation treatment. Sludge will need to be solidified/stabilized. Cost estimated excludes precipitation cost.
Thermal	Wet Air Oxidation	Full-scale. Not applicable to metal removal.	NA		Oxidation of metal ions is incidental to using this process on groundwater.
	Supercritical Oxidation	Full-scale. Not applicable to metal removal.	NA		Oxidation of metal ions is incidental to using this process on groundwater.
	Incineration	Not applicable to metal contaminated groundwater.	NA		
Biological	Biological Activated Carbon	Not applicable to metal removal.	NA	4	GAC would be more appropriate use of activated carbon for metals.
	Aquaculture	Full-scale for organics.	Unavailable		Separation treatment Contaminated plants may need special treatment. Other limitations make this an unlikely option.
	Bioaccumulation of Metals	Pilot/bench-scale.	Unavailable		Separation treatment. Treatment of sludge required.

TABLE B.6. Volatile Organic Compounds-Contaminated Groundwater Developmental Treatment Technologies

Treatment Category	Treatment Technologies	Development/Feasibility Status	Cost Range ($/Ton)	Cost Range Reference	Comments
Physical/ Chemical	Resin Adsorption	Full/pilot-scale.	≤1 to 20	2, 5	Separation treatment. Concentrated regeneration stream needs treatment.
	Carbon Adsorption	Full-scale.	≤1 to 20	5	Separation treatment. Carbon cannot be regenerated and must be disposed.
	Reverse Osmosis/Membrane Separation	Full-scale; potentially applicable to organic molecules with a molecular wt. ≥100.	1 to 20	7, 15, 24	Separation treatment. Concentrated waste stream must be further treated.
	Chemical Oxidation (Free Radical Oxidation)	Full-scale.	≤1 to 4	2, 10, 14	Destroys organics - may leave secondary products. Includes ozone, H_2O_2 (with catalyst) and $KMnO_4$. Applicable to wastewater - May oxidize solids. Ozone and H_2O_2 may be assisted by UV or ultrasonics.
	Air/Steam Stripping	Full-scale.	≤1 to 24	2, 7, 14	Separation treatment. Contaminated gas must be treated.
	Distillation/Evaporation Systems	Full-scale.	≤3 to 10	2, 7	Separation treatment. Residual bottoms, and overhead vapor may require further treatment.
	Organic Solvent Extraction	Full-scale.	≤5 to 30	2	Separation treatment. Costs generally include treatment to recover solvent from treated water prior to discharge using air/steam stripping.
	In Situ Surfactant Complexing	Not tested on VOCs. Probably not feasible for many VOCs.	NA		Precipitates EXPs. Complex may be more hazardous. Large quantities of surfactant required. Does not treat EXPs degradation compounds.
	Base-Initiated Reduction	Bench-scale; under development by USATHAMA for EXPs. Probably not applicable to VOCs.	NA		
	Freeze Crystallization	Pilot/full-scale.	20 to 100	7, 10, 20	Separation treatment. Concentrated aqueous waste stream needs further treatment. Generally removes all impurities equally well.
	Catalytic Destruction	Bench-scale.	20 to 30	1	Destroys organics. More applicable to wastewater, pumpable sludge containing 1% to 10% organics. High pressure (3000 psi) required.

TABLE B.6. (contd)

Treatment Category	Treatment Technologies	Development/Feasibility Status	Cost Range ($/Ton)	Reference	Comments
Thermal	Supercritical Water Oxidation	Full-scale.	170 to 1000	7	Destroys organics including EXPs.
	Wet Air Oxidation	Full-scale.	60 to 260	2, 20	Incompletely destroys organics. Liquid effluent must be further treated. Moderate to high pressure required. Waste must be pumpable.
Biological	Biological Activated Carbon	Full-scale.	6 to 31	20	Destroys organics. Tolerates higher concentrations of organics. Must thermally regenerate carbon.
	Bioreactors	Full-scale.	5 to 10	(a)	Destroys organics. Generates sludge.
	In Situ Biotreatment	Bench/Pilot-scale.	125	19	Destroys organics. Very limited data for organics.
	Enzyme Destruction	Lab-scale.	Unavailable	7	Destroys specific compounds. Generates secondary products. Each enzyme effective for single compound.

(a) Vendor information from Chemical Waste Management, Inc., Newark, California; Casmalia Resources, Santa Barbara, California; Environsafe Service of Idaho, Grand View, Idaho.

TABLE B.7. Potential Treatment Technologies

	Technology Category			
Remedial Action Category	Physical	Chemical	Thermal	Biological
SOIL				
Explosives		Soil Washing Chemical Destruction		Composting In Situ Treatment
Heavy Metals	In Place Stabilization	Soil Washing/Stabilization In Situ Flushing	Roasting, ISV Molten Glass	Soil Washing/Bioaccumulation
Volatile Organic Compounds		Soil Washing Chemical Destruction	LTTS In Situ Heating Steam Stripping	In Situ Treatment
GROUNDWATER				
Explosives (onsite)	Resin Adsorbent	Chemical Oxidation Catalytic Destruction UV/Ozone Oxidation		Bioreactor
Explosive (in situ)				In Situ Treatment
Heavy Metals (onsite)	Activated Carbon/ Adsorbents			Bioaccumulation
Volatile Organic Compounds (in situ)		UV/Ozone Oxidation Chemical Oxidation Catalytic Destruction		
Volatile Organic Compounds (in situ)				In Situ Treatment

B.2 REFERENCES FOR TABLES B.1 THROUGH B.6

1. Baker, E. G., L. J. Sealock, Jr., R. S. Butner, D. C. Elliott, G. G. Neuenshcwander, and N. G. Banns. 1989. "Catalytic Destruction of Hazardous Organics in Aqueous Wastes: Continuous Reactor System Experiments," Hazardous Waste & Hazardous Materials 6(1):87-93.

2. Breton, M, P. Frillici, S. Palmer, C. Spears, M. Arienti, M. Kravett, A. Shayer, N. Suprenant 1988. Treatment Technologies for Solvent Containing Wastes, Noyes Data Corp., Park Ridge, New Jersey.

3. Buelt, J. L., and J. G. Carter. 1986. Description and Capabilities of the Large-Scale In Situ Vitrification Process. PNL-5738, Pacific Northwest Laboratory, Richland, Washington.

4. Camp Dresser & McKee Inc. 1986. Superfund Treatment Technologies: A Vender Survey. EPA/540/2-86/004(f). U.S. Environmental Protection Agency, Washington D.C.

5. De Renzo, D. J. 1978. Unit Operations for Treatment of Hazardous Industrial Wastes. Noyes Data Corp., Park Ridge, Tennessee.

6. Freeman, H. M. 1986. Innovative Thermal Processes for Treating Hazardous Wastes. Technomic Publishing Co., Inc., Lancastor, Pennsylvania.

7. Freeman, H. M. 1989. Standard Handbook of Hazardous Waste Treatment and Disposal. McGraw-HIll, New York, New York.

8. Hazardous Waste Engineering Research Laboratory. 1985. Handbook of Remedial Action at Waste Disposal Sites (Revised). EPA/625/6-85/006, U.S. Environmental Protection Agency, Cincinnati, Ohio.

9. Hazardous Waste Engineering Research Laboratory. 1986. Hazardous Waste Treatment Technology. PB86-145539, U.S. Environmental Protection Agency, Cincinnati, Ohio.

10. HazTECH News, August 25, 1989.

11. Johnson, N. P., and M. G. Cosmos. 1989. "Thermal Treatment Technologies for Haz Waste Remediation," Pollution Engineering 21(11):67-85.

12. Koegler, S. S., R. K. Farnsworth, R. K. Nakaoka, J. M. Perez, and C. L. Timmerman. 1989. Vitrification Technologies for Weldon Springs Raffinate Sludges and Contaminated Soils, Phase 2 Report: Screening of Alternatives. PNL-7125, Pacific Northwest Laboratory, Richland, Washington.

13. "Low-Cost Cleanup of Toxic Petrochemicals." C&EN, December 12, 1988.

14. McArdle, J. L. 1987. Handbook on Treatment of Hazardous Waste Leachate. PB87-152328. U.S. Environmental Protection Agency, Cincinnati, Ohio.

15. "Membrane-Like Material Developed to Remove Oil, Chlorinated Organics from Wastewater." HazTech News 4(8):1, April 20, 1989.

16. Nunno, T. J., J. A. Hyman, and T. H. Pheiffer. 1988. Assessment of International Technologies for Superfund Applications. EPA/540/2-88/003, U.S. Environmental Protection Agency, Cincinnati, Ohio.

17. Oma, K. H., and J. L. Buelt. 1989. "In Situ Heating to Detoxify Organic-Contaminated Soils." Hazardous Materials Control 2(2):14-19.

18. Oppelt, T. E. 1987. "Incineration of Hazardous Waste: A Critical Review." Journal of Air Pollution Control Association 37(5):558-586.

19. Pheiffer, T. H. 1989, "EPA's Assessment of European Contaminated Soil Treatment Techniques." Presented at AICHE Summer National Meeting, Philadelphia Pennsylvania, August 20-23, 1989.

20. Site Cleanup Technologies Summary of Responses to July 1988 Solicitation of Interest. 1989. Remedial Technology Assessment Program, Department of Health Services, State of California, Sacramento.

21. Sawyer, S. 1989. Volume I - Technology Evaluation Report, Site Program Demonstration Test, HAZCON Solidification, Douglassville, Pennsylvania. EPA/540/5-98/001a. U.S. Environmental Protection Agency, Cincinnati, Ohio.

22. Torpy, M. F., H. F. Stroo, and G. Baker. 1989. "Biological Treatment of Hazardous Waste." Pollution Engineering 21(5):80-86.

23. Unterberg, W., R. W. Melvold, S. L. Davis, F. J. Stephens, and F. G. Bush III. 1987. Reference Manual of Countermeasures for Hazardous Substances Releases. EPA/600/2-87/069, U.S. Environmental Protection Agency, Cincinnati, Ohio.

24. Weber, W. F., and W. Bowman. 1986. "Membranes Replacing Other Separation Technologies." Chemical Engineering Progress November 1986.

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